REPORT NUMBER: WI/SPR-06-01

STRATEGIES FOR ENHANCING THE FREEZE-THAW DURABILITY OF PORTLAND CEMENT CONCRETE PAVEMENTS

FINAL REPORT

WISCONSIN DEPARTMENT OF TRANSPORTATION

TECHNOLOGY ADVANCEMENT

JULY 2001

Technical Report Documentation Page

1. Report No. WI/SPR-06-01	**2. Government Accession No.**	**3. Recipients Catalog No.**
4. Title and Subtitle Strategies for Enhancing the Freeze-Thaw Durability of Portland Cement Concrete Pavements		**5. Report Date** July 2001 **6. Performing Organization Code**
7. Author(s) S. M. Cramer R. A. Walls, Jr.		**8. Performing Organization Report No.**
9. Performing Organization Name and Address University of Wisconsin - Madison Department of Civil and Environmental Engineering 1415 Engineering Drive, Madison, WI 53706-1490		**10. Work Unit No. (TRAIS)** **11. Contract or Grant No.** WisDOT SPR # 0092-45-76
12. Sponsoring Agency Name and Address Wisconsin Department of Transportation Division of Transportation Infrastructure Developmet Bureau of Highway Construction Technology Advancement Unit 3502 Kinsman Blvd., Madison, WI 53704-2507		**13. Type of Report and Period Covered** Final Report; 1997-2001 **14. Sponsoring Agency Code** WisDOT Study # 95-02
15. Supplementary Notes		

16. Abstract

Use of fly ash and ground granulated blast furnace slag as partial portland cement replacement materials continues to grow, driven by recycling issues, occasional cement shortages, and simple initial cost economics. This laboratory study examined the freeze/thaw durability of concrete specimens containing these additives with water-cementitious material ratios ranging from 0.30 to 0.45 and air contents ranging from no entrained air to a target 7.0 percent air. ASTM 666 accelerated freeze-thaw testing in a sodium chloride solution with measurements of the dynamic modulus of elasticity and weight loss were the primary evaluation methods for the concrete. Because of the latent hydraulic activity imparted by the mineral additives, specimens were allowed to cure for 56-days before the testing regime began. Freeze-thaw testing then proceeded for an extended period up to 1500 cycles. Results showed that air content overwhelming determined the freeze-thaw durability of these mixtures and that w/cm had no identifiable influence for w/cm as low 0.30. WisDOT Grade A-FA concrete with 18.6 percent fly ash by weight displayed superior durability to a comparable WisDOT Grade A mix. The 50 percent granulated blast furnace slag mixes (Grade A-S) had durability comparable to the Grade A mix. Water-cementitious material ratio played a dominant role in strength development and will affect traffic opening on new pavements. This research has shown that ensuring an adequate air void system is crucial to concrete longevity.

17. Key Words Concrete, fly ash, ground granulated blast furnace slag, water-cement ratio, entrained air	**18. Distribution Statement**

19. Security Classif. (of this report)	**19. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**

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JULY 2001

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1. Problem Statement

Wisconsin Department of Transportation (WisDOT) portland cement concrete (PCC) pavements have had a typical service life of 20 to 30 years. There is potential to increase the service life of these pavements by addressing durability problems primarily manifested by freeze-thaw related deterioration at cracks and joints.

2. Objectives and Scope of the Study

The objective of this study was to establish concrete mix performance data to identify ways to increase the service life of portland cement concrete pavements by improving the durability of WisDOT paving mixes and to reduce durability related deterioration exhibited at joints. The study focused on the tradeoffs between air content and water-cementitious material ratio (w/cm) in freeze-thaw durability and compressive strength. The main hypothesis was that decreased w/cm would lead to increased strength and significant increases in durability. The research plan sought to quantify this potential increase achieved through careful control of water and increased cement and/or cementitious material additions to the mix.

The research consisted of three phases: an initial literature survey, controlled laboratory tests of concrete mixes containing mineral additives and data analysis. The research was limited to the evaluation of different portland cement concrete mixes that are currently, or could be expected to be, applied in Wisconsin road construction. Fly ash and ground granulated blast furnace slag (GGBFS) were used individually as partial replacements for Type I portland cement. Twenty-three (23) different mixes were evaluated. Freeze-thaw testing followed a modified ASTM protocol that significantly extended evaluation typically reported, providing a more complete and realistic picture of mix freeze-thaw durability.

Results obtained from the research were considered in light of the economic impact and potential increased service life that can be expected from a pavement. Such an interpretation is not direct and includes many assumptions. None-the-less, it is a starting point in quantifying the impact of these results on actual field performance.

3. Background

Pertinent literature on freeze-thaw durability was reviewed as the first phase of this research. The bibliography for this review is contained in Appendix I. The literature divides freeze-thaw distress into two categories; internal cracking leading to a decrease in the elastic modulus, and surface scaling where the outer surfaces of the concrete are eroded with increasing exposure.

The findings from the bibliography are summarized in Appendix II. There is conflicting evidence concerning the relative benefit of a low w/cm on concrete freeze-thaw durability, especially as it relates to the amount of additional entrained air (that beyond the intrinsic air content) needed in combination with the low water cement ratio. Relevant research includes that of Yamato et al. (86, see Appendix I), Li et al. (37), Kashi and Weyers (31), and Pigeon and Marchand (63) who have found that concrete with a low water-cement ratio does not require additional entrained air for freeze-thaw protection. What constitutes a “low” water-cement ratio sufficient to diminish the need for additional entrained air is generally 0.30 or less with some investigators working with 0.25. However, data also exist demonstrating that a low w/c is not sufficient to eliminate or significantly reduce the need for purposely-entrained air. Malhotra’s reports (43 and 45) indicate that all non-entrained specimens failed ASTM C666, Procedures A and B, regardless of the w/c used. Cohen et al. (12) found entrained air was required for mixes with w/c of 0.35 and Miura and Itabashi (52) have shown that w/c's greater than 0.25 have proven to be ineffective at sustaining high durability over greater levels of freeze-thaw cycling with no entrained air. Many factors may be attributed to these apparent contradictions due to the complexity of freeze-thaw mechanisms of deterioration including the degree of saturation forwarded by MacInnis and Beadoin (39) and Fagerlund (16), and the number of freeze-thaw cycles at which the evaluation is made. Pigeon and Pleau (65) discuss the tradeoff of the positive effect of the reduced amount of freezable water as w/cm decreases and the negative effect of reduced permeability. They also discuss the concept of critical spacing factor for air voids as that if exceeded for any given concrete and exposure condition will lead to rapid deterioration of the concrete. Data presented by Pigeon (58) shows that the critical spacing factor ranges from 0.20 mm to values as high as 0.40 mm as the w/c is decreased to 0.30 and 0.750 mm for w/c of 0.25.

From the literature we made the following general observations:

- A direct relation between decreased permeability and increased or decreased freeze-thaw durability has not been established despite the frequent assumption that such a relationship exists.
- Just making concrete less permeable does not by itself ensure high freeze-thaw durability.
- Decreasing w/cm has been argued and in some cases shown to improve freeze-thaw durability.
- Air void spacing factors in the range of 0.20 to 0.40 mm are sufficient to provide freeze/thaw durability. Additional entrained air that provides spacing factors less than 0.20 to 0.40 mm may not yield significant improvements in freeze-thaw durability.
- Substitutions of portland cement with fly ash reduce permeability but do not necessarily improve freeze-thaw durability to levels comparable to the durability of ordinary portland cement mixes.

4. Methodology and Testing Regime

4.1 General

Two series of mixes dominated the testing. The first series consisted of a Grade A-FA WisDOT paving mix containing 18.6% Class C fly ash as a by-weight replacement for Type I portland cement. The second series used a 50% by weight replacement of portland cement with Grade 100 GGBFS, Grade A-S. Two mixes were eventually added to this series that employed 20% and 40% cement replacements with GGBFS respectively. A standard all cement mix (WisDOT Grade A) was also added to the test matrix for comparison and two mixes in the fly ash series were remixed and retested as described later. The full regime of tests were not conducted on specimens for all of the additional mixes. Two variables dominated the evaluation of each mix series, the water-cementitious material ratio and the air content. The w/cm values were 0.45, 0.4, 0.35, and 0.30 and three target air levels of no purposely-entrained air, 4% and 7% were evaluated. Table 1 summarizes the testing program.

These mixes were evaluated with the series of tests listed in Table 2. The primary tests were air void analysis, accelerated freeze-thaw testing and compressive strength. The accelerated freeze-thaw testing was conducted with a modified procedure that included 3% sodium chloride solution and extended cycling to 1500 cycles.

Table 1. Mixes evaluated with target air contents

Target air content	WATER-CEMENTITIOUS MATERIAL RATIO AND ADDITIVE TYPE								
	0.45		0.40			0.35		0.30	
	Fly Ash	GGBFS	No additive	Fly Ash	GGBFS	Fly Ash	GGBFS	Fly Ash	GGBFS
No air entrainment				FA2	S2			FA7	S7
4%			A	FA3	S3 S10 20% S11 40%	FA5	S5	FA8 FA8b	S8
7%	FA1	S1		FA4 FA4b	S4	FA6	S6	FA9	S9

Table 2. Summary of Tests Performed

Test	Frequency	Applicable ASTM Standard	Curing Conditions	Age of Concrete at Test (days)
Slump	1 per batch	C143	NA	0
Plastic Air Content	1 per batch	C231	NA	0
Unit Weight	1 per batch	C138	NA	0
Air Void Analysis	1 per mix	C457	NA	NA
Accelerated Freeze-Thaw	3 per mix	C666	56 day wet	Begin cycles at 56 days
Rapid Chloride Ion Penetration	2 per mix	C1202	Approx. 250 days	Approx. 250 days
Compressive Strength	20 per mix	C39	3, 7, 28, 56 and 365 days wet	3, 7, 28, 56 and 365 days
Air Dry Shrinkage	3 per mix	C490, C157 modified	14 day wet	NA
Petrography	Selected mixes	C856	56 day wet + f/t test period	After f/t test

4.2 Materials

The natural aggregates used throughout the project were obtained from a local quarry in Southern Wisconsin. The coarse aggregate was a 19.1-mm crushed limestone conforming to AASHTO #57. The fine aggregate was river sand that conformed to WisDOT specifications. The coarse aggregate had a specific gravity of 2.68 and an absorption of 1.1%. The fine aggregate had a specific gravity of 2.63 and an absorption of 1.3%.

The Type I portland cement used in the research was a moderate alkali (0.65 Na_2O_3) cement conforming to ASTM C150. The Class C fly ash was obtained in one shipment from one source and was characterized according to ASTM C618. Commercial Grade 100 GGBFS was obtained in one shipment. The chemical compositions for the cementitious materials are shown in Appendix III.

The air entrainment used was Daravair 1400[1], a wood rosin based admixture, and Daracem 19, a high range water reducer consisting of a modified naphthalene sulfonate, was used to control water demand.

4.3 Mix Design and Specimen Preparation

WisDOT Grade A-FA and A-S concrete mixes formed the basis of the mix designs. The Grade A-FA uses an 18.6% by weight cement replacement with fly ash (WisDOT 1996). The Grade A-S mix uses a 50% by weight cement replacement with GGBFS. A Grade A mix was also prepared for comparison. The fine aggregate made up a fixed 42% of the total aggregate weight for each mix. A fixed weight of water was added to each batch early in the mixing process to achieve the target w/cm and no additional water was added. Air entrainment and high range water reducer were added as needed to achieve air content and adequate workability. Table 3 shows the mix design quantities. Mixes were prepared in 0.088 m^3 batch sizes in a 0.17 m^3 drum mixer following ASTM C192 standard procedures.

Solid volume concepts suggest that as cement content changes, so should aggregate contents (Table 3). The computed changes in aggregate quantities were in the range of 1% to 3% and thus in the context of the preparation of 0.088 m^3 batch sizes these differences were ignored.

Table 3. Mix Design Material Weights

	A (kg/m^3)	**FA1 – FA9 (kg/m^3)**	**FA8b (kg/m^3)**	**S1 – S6 (kg/m^3)**	**S7 – S9 (kg/m^3)**	**S10 (kg/m^3)**	**S11 (kg/m^3)**
Portland cement	338	285	332	169	195	271	205
Class C fly ash	0	65	76	0	0	0	0
Grade 100 GGBFS	0	0	0	169	195	68	135
Fine Aggregate	771	762	762	771	771	771	771
Coarse Aggregate	1065	1053	1053	1065	1065	1065	1065

Low w/cm mixes in the fly ash series (FA1-FA9) were achieved through appropriate dosages of high range water reducer. Mix FA8b was prepared to check the influence of achieving the same 0.30 w/cm through the addition of more cementitious materials and less high range water reducer. Low w/cm mixes in the slag series were achieved with higher proportions of cement and GGBFS.

Prior to casting specimens, slump, air content using the pressure method and unit weight were recorded for each batch. Extraordinary care was used in each test to ensure it was performed the same throughout the research program. Aggregate air corrections (ASTM C231) were measured and used to adjust plastic mix air contents.

Specimens were cast in cylinders and prisms according to ASTM C192. Five freeze-thaw specimens were cast in metal forms for freeze-thaw testing, air void analysis and petrography. Twenty-two 102-mm diameter by 203-mm in length cylinders were cast in plastic forms for permeability and compressive strength testing. Three shrinkage specimens (203-mm by 102-mm by 76-mm) were also cast in metal

[1] Commercial trade names are listed for completeness and do not imply product endorsement.

forms. After mixing, all specimens were covered with wet burlap for one day and cylinder molds were capped with plastic covers to retain moisture and the cylindrical shape.

Forms were removed after one day. Cylinder specimens were weighed, labeled and the average diameter was recorded with a Pi tape. All specimens were then placed in a curing room and cured at 100% relative humidity with a temperature of approximately 21 °C up to the time of testing.

4.4 Test Methods

Testing of the hardened concrete was carried out following the tests and standards listed in Table 2. Deviations from these test procedures were targeted to the objectives of the research.

Freeze-thaw testing was conducted in general compliance with ASTM C666 Procedure A with transverse frequency and weight loss monitored to assess the degree of degradation up to 1500 cycles. A 56-day curing period was used to allow the hydration of fly ash and GGBFS mixes to reach a minimum level representative of actual field conditions. As expected this resulted in concrete that was extremely durable compared to the 14-day curing regime often used with ASTM C666. Following the 56-day curing period, specimens scheduled for freeze-thaw durability testing were placed in a freezer and kept below 0°C (32°F) to minimize environmental impacts and regulate relative time for curing. Specimens remained in the freezer up to the time of testing. The specimens were then thawed in air for 24 hours and soaked for 48 hours in a 3% sodium chloride solution. Accelerated freeze-thaw chambers were used which kept the samples immersed in the sodium chloride solution and cycled between –18°C (0°F) and 10°C (50°F) at an average rate of 6 cycles per day.

Transverse frequency testing for the calculation of dynamic modulus was conducted at least every 36 cycles in addition to weight loss. The dynamic modulus of elasticity was the basis of computing relative durability. Visual inspections of specimen degrade were made at each testing. Specimens were considered failed and removed from testing when their relative dynamic modulus fell below 60%. The relative dynamic modulus of elasticity and the relative weight loss were computed each time with the 0 cycle reading providing the basis. The readings for the three specimens from the same batch were averaged. These averages at 300, 600, 900, 1200 and 1500 cycles were selected to represent the complete freeze/thaw history in data analysis.

Concrete permeabilities were inferred by measuring the movement of chloride ions through concrete as contained in ASTM C1202. In this procedure, specimens were cut approximately 2 inches in thickness using a masonry saw with a diamond tip blade from a previously cast cylinder at a specific age. The specimens were then conditioned by placing a coating of non-conductive epoxy on the remaining outer surface. Subsequently the specimens were then subjected to three hours of vacuum (pressure < 1 mm Hg)[air dry] and on additional hour of vacuum [under de-aired water], followed by 18 hours of soaking in water. The test consisted of monitoring the amount of electrical current passed through 102 mm (4 in.) diameter by 51 mm (2 in.) long vacuum-saturated concrete specimen when one side of the specimen is immersed in a NaCl solution and the other side in a NaOH solution and a potential difference of 60V dc was maintained on the specimen for 6 hours. The total charge passed, in coulombs, was related to chloride penetrability of the specimen.

Based on the successful laboratory studies by the Florida DOT, results of the rapid chloride ion permeability test were found to be linearly related to the water permeabilities. Thus the chloride ion penetrability test was assumed to provide a relative measurement of permeability that can be used as an indicator of the quality and performance characteristics of concrete.

Compressive strengths were measured at 3, 7, 28, 56 and 365 days according to ASTM C39. Prior to testing, a sulfur-based capping compound (ASTM C617) was used to provide a uniform testing surface for the cylinder. The specimen was then loaded at a constant rate of 13 MPa/min (1885 psi/min) until failure (5% loss in load), with the peak load recorded. The peak loads were then used in conjunction with the diameter measured using the Pi tape to calculate the maximum compressive stress the cylinder experienced.

Air void parameter analysis and petrographic examination were performed by third parties under contract with the University of Wisconsin-Madison. Air void parameter analysis was used to determine the characteristics of the hardened internal structure of the specimens per ASTM C457, Procedure A. Petrographic analyses were performed according to ASTM C856 to determine the possible failure mode of each specimen after freeze-thaw exposure. The petrographic analysis was not conducted on all specimens after initial analyses did not reveal meaningful information.

5. Test Results

5.1 Plastic Concrete Results

Results from the fresh concrete tests and air void analysis are shown in Table 4. Slumps were restricted to the range of 25 to 75 mm. Target air contents were sought for no air entrainment, 4% and 7% as shown in Table 1. Mix FA-4b was prepared after mix FA-4 showed an unusual deviation between the plastic and hardened air contents.

5.2 Correlations with Freeze-thaw Durability and Other Performance Measures

As the primary focus of the research was on freeze-thaw durability, the test results were examined to identify those parameters that most strongly correlated with freeze-thaw durability. Correlations were computed parameter by parameter with freeze-thaw durability and weight loss as shown in Table 5. The correlations between air content from the air void analysis and the plastic air content measured by the pressure method are also shown. A strong correlation is expected but the values emphasize that the correlation is not perfect and therefore the hardened air content is used in all subsequent data analysis. GGBFS mixes showed stronger correlations between plastic and hardened air. Correlation coefficients for durability degrade and average weight loss were computed at 300, 600, 900, 1200 and 1500 cycles of exposure and then averaged. With the exception of weight loss in the fly ash mixes, hardened air content showed a stronger correlation to durability degrade and weight loss compared to plastic air content. Spacing factor generally had the strongest correlations with durability degrade and weight loss.

Correlations between other parameters are shown in Table 6. The purpose of these correlations is to indicate which parameters are dependent on other parameters such that secondary relationships to freeze-thaw durability and strength can be established. These correlations indicate the multivariate nature of concrete mix optimization. No one parameter is a perfect predictor of concrete performance. There is a variety of counteracting parameters that influence any one performance measure.

Table 4. Plastic concrete test results and hardened air content

Mix	w/cm	Slump (mm)	Unit weight (kg/m^3)	Plastic Air Content (%)	Hardened Air Content (%)	Spacing Factor (mm)
A	0.40	NA	NA	3.9	5.0	0.23
FA-1	0.45	25	2213	7.3	8.3	0.10
FA-2	0.40	40	2360	1.4	1.8	0.69
FA-3	0.40	60	2275	3.9	3.7	0.23
FA-4	0.40	60	2440	6.3	4.0	0.20
FA-4b	0.40	NA	NA	6.1	7.3	0.13
FA-5	0.35	50	2340	4.2	3.9	0.25
FA-6	0.35	65	2215	7.4	4.7	0.20
FA-7	0.30	25	2455	2.0	2.6	0.53
FA-8	0.30	60	2390	4.1	3.2	0.30
FA-8b	0.30	NA	NA	3.5	4.4	0.23
FA-9	0.30	30	2300	7.3	5.8	0.28
S-1	0.45	60	2239	6.9	7.0	0.13
S-2	0.40	40	2410	1.8	0.9	0.81
S-3	0.40	50	2330	4.2	3.0	0.33
S-4	0.40	45	2265	6.9	6.1	0.18
S-5	0.35	40	2345	3.6	3.3	0.38
S-6	0.35	70	2310	7.2	6.4	0.18
S-7	0.30	75	2440	1.7	2.9	0.76
S-8	0.30	50	2315	3.8	4.2	0.25
S-9	0.30	65	2225	7.2	8.1	0.13
S-10	0.40	15	2344	4.0	5.1	0.23
S-11	0.40	15	2328	3.9	4.8	0.25

Table 5. Correlation Coefficients of Mix Parameters on Freeze-thaw Durability

Parameter	Plastic air content		Average F/T Durability		Average F/T Weight	
	Fly ash	GGBFS	Fly ash	GGBFS	Fly ash	GGBFS
w/cm			0.38	-0.19	0.47	-0.30
Plastic air content	1.00	1.00	0.74	0.45	0.71	0.58
Hardened air content	0.80	0.93	0.79	0.48	0.50	0.72
Spacing Factor			-0.78	-0.57	-0.72	-0.79
RCP (Rapid Chloride Ion Penetration)			0.49	0.23	0.71	0.45
Percent Shrinkage at 28 days			-0.63	-0.51	-0.21	-0.54

Table 6. Correlation Coefficients of Mix Parameters on Other Performance Measures

Parameter	RCP – Rapid Chloride Ion Penetration		Shrinkage – 28 days		Compressive Strength	
	Fly ash	GGBFS	Fly ash	GGBFS	Fly ash	GGBFS
w/cm	0.69	0.20	-0.51	-0.27	-0.90	-0.67
Plastic air content	0.55	0.81	-0.44	-0.69	-0.57	-0.74
Hardened air content	0.35	0.94	0.80	-0.75	-0.65	-0.62
Spacing Factor	-0.34	-0.81	0.47	0.67	0.65	0.66
RCP	1.00	1.00	-0.56	-0.73	-0.64	-0.72
Percent Shrinkage at 28 days	-0.56	-0.73	1.00	1.00	0.57	0.51

5.3 Freeze-Thaw Durability

Freeze-thaw durabilities were assessed by averaging dynamic modulus of elasticity and weight loss from three specimens for each mix. The standard deviations from these measurements were within or very close to Within Laboratory Precisions specified in ASTM C666. Averages established at 0, 300, 600, 900, 1200 and 1500 cycles were chosen to represent readings gathered every 36 cycles.

Correlations of w/cm ratio with freeze-thaw durability degrade and weight loss were very weak (Table 5). Plastic air and hardened air contents displayed strong correlations as expected with hardened air content providing a stronger correlation. Spacing factor correlations with durability were even higher but were not used for data analysis because of the inability to readily measure spacing factor either directly or indirectly. Based on the correlation results, data analysis focused on the relationship of durability with hardened air content.

Figure 1 shows relative durability for the Grade A and the fly ash mix series plotted against hardened air content. Increasing symbol size in Figure 1 represents higher number of cycles. Figure 1 shows that independent of w/cm, mixes with high air contents show considerably less degrade in durability than mixes with lower air contents. The no fly ash, Grade A mix fits the general trend of the data. Mix FA8b was constructed using additional cementitious content as opposed to Mix FA8 achieved through use of high range water reducer and limited water. Mix FA8b displayed higher durability than Mix FA8, but Mix FA8b had a higher air content and the additional difference in freeze/thaw durability may be due to this difference. As air content decreases from just above 3.5%, the durabilities decrease predictably as indicated from the results in Fig. 1. Figure 2 shows the same data as in Fig.1 plotted based on spacing factor. The benefit of reduced spacing factor continues unabated to spacing factors as small as approximately 0.1 mm.

Relative weight loss for Mix A and the fly ash mix series are shown in Figure 3 plotted against hardened air content. As in Fig. 1, increasing symbol size in Figure 3 represents higher number of cycles. Weight loss occurs relatively slowly compared to degrade in modulus of elasticity but a decrease of 10% in weight will show extensive loss of specimen surfaces. Some of the most durable specimens may show an increase in weight resulting from increased levels of saturation with little or no scaling loss of surface paste. As shown in Fig. 2, weight losses with increasing cycles of exposure increase gradually as air decreases to 3%. At air contents less than 3%, weight losses increase dramatically. The results in Fig. 2, clearly show the no fly ash, Grade A mix displaying much greater weight loss than the fly ash mixes.

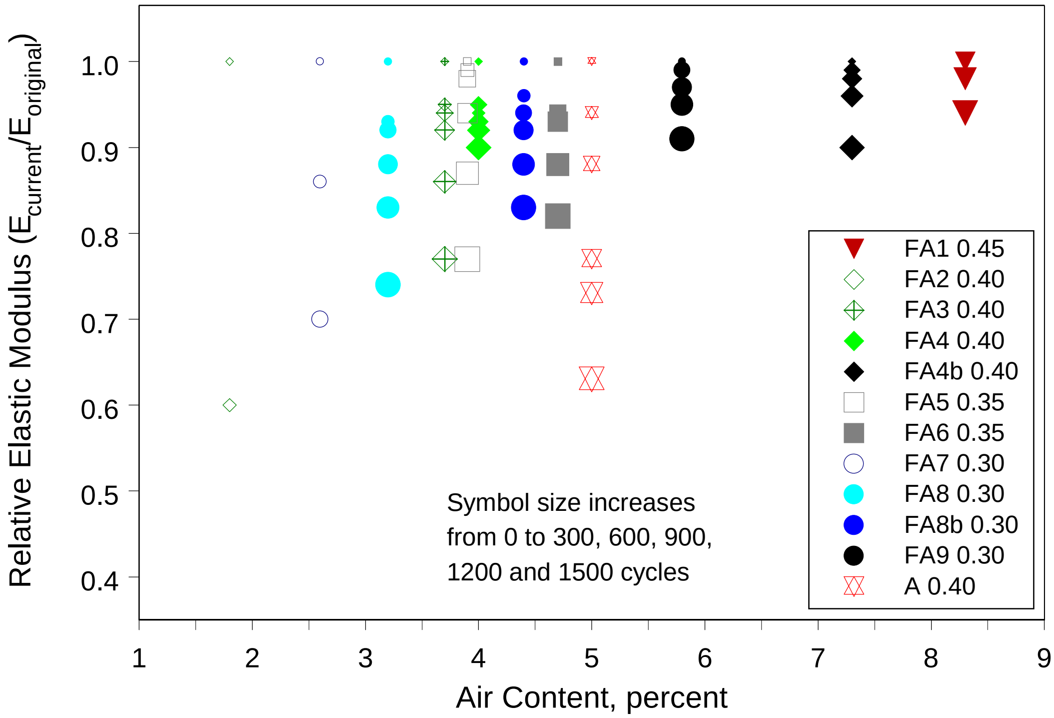

Figure 1. Relative durability of fly ash and Grade A mixes with the respective w/cm shown in the legend.

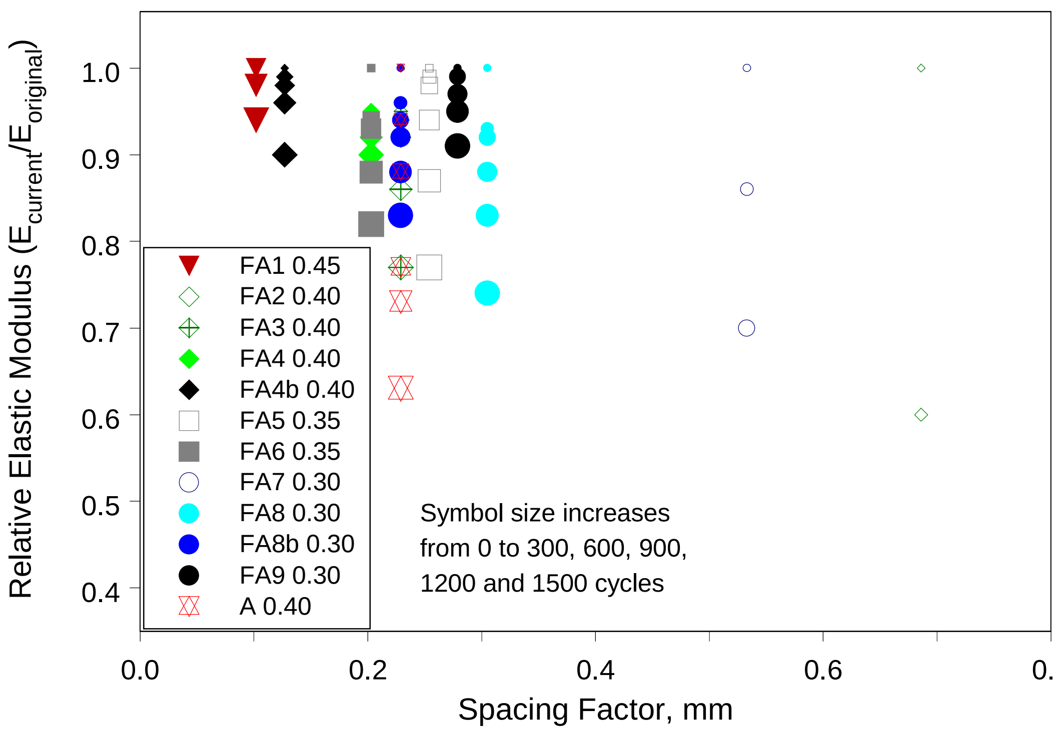

Figure 2. Relative durability of fly ash and Grade A mixes based on air void spacing factor.

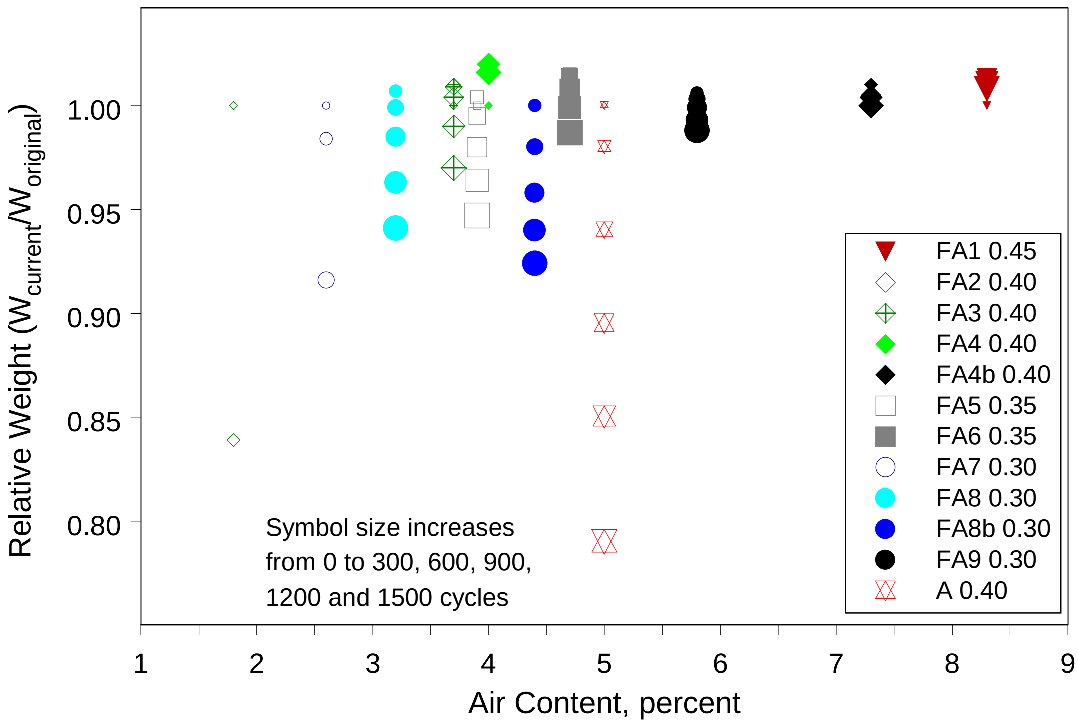

Figure 3. Relative weight loss of fly ash and Grade A mixes.

Similar analysis of freeze-thaw data was conducted for the GGBFS series of mixes. Figure 4 shows relative durability versus hardened air content for this series. Degrade of durability is comparable for air contents in the range of 3% to 8% air. Air contents of less than 3% were associated with specimens exhibiting rapid failure. Between 3% to 8% air content the dependence of durability on air content was strong through 1200 cycles, but the correlation broke down at 1500 cycles of exposure. The difference between the influence of air content on durability for the fly ash series mixes (Figure 1) and that for the GGBFS mixes (Figure 5) at 1500 cycles of exposure is striking. Consideration of durability based on spacing factor (Fig. 6) provides no clarity to trends of the data. Spacing factors of 0.1 to 0.4 mm overall provided comparable levels of durability. The quantity of GGBFS replacing cement (S10 at 20% vs. S11 at 40% vs. others at 50%) did not appear to influence the relative durabilities and the rates of durability degrade.

Relative weight loss versus hardened air content is shown in Figure 6 for the GGBFS series mixes. As air content dropped below 6%, weight loss increased significantly with the exception of apparent outlier data. Benefits of air contents up to and exceeding 8% are observed in Figure 6. Examining relative weight loss versus spacing factor (not shown) brings slightly more order to the data trends but does not change the overall picture. Weight loss with 20% GGBFS replacement of cement showed slightly less weight loss than higher GGBFS levels. With the exception of the low air, 0.30 w/cm mix, the 0.3 and 0.35 w/cm ratios appeared to result in lower weight losses than the 0.40 w/cm mixes. This observation was not confirmed by the correlation coefficients in Table 6.

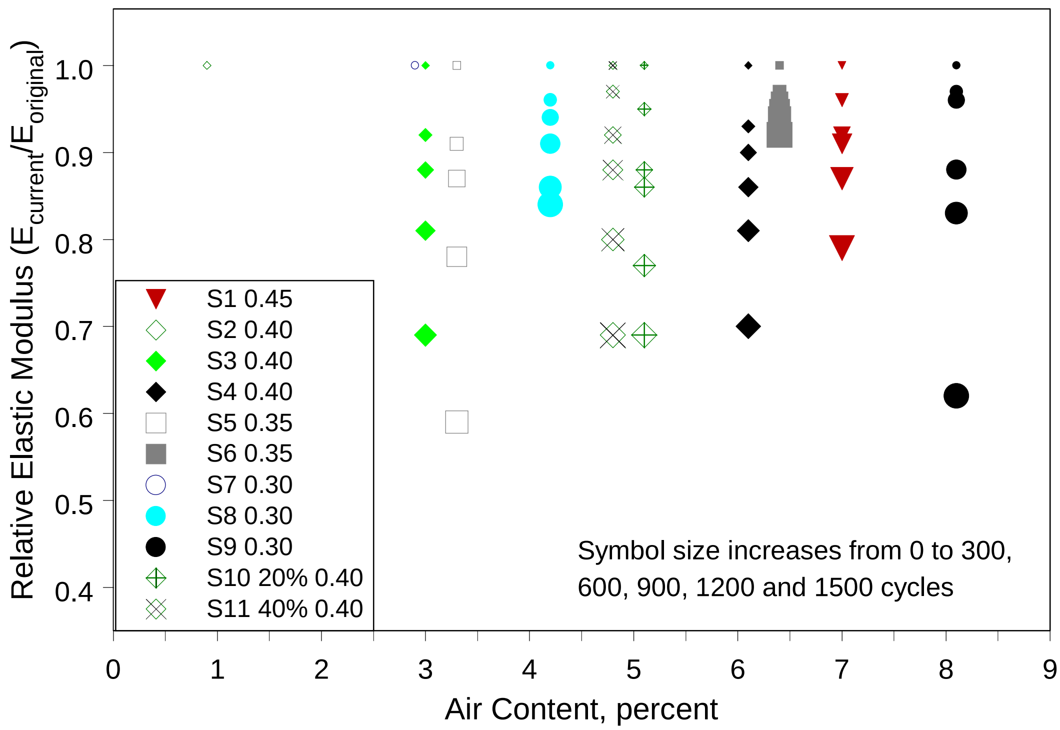

Figure 4. Relative durability of GGBFS series mixes with the respective w/cm identified in the legend.

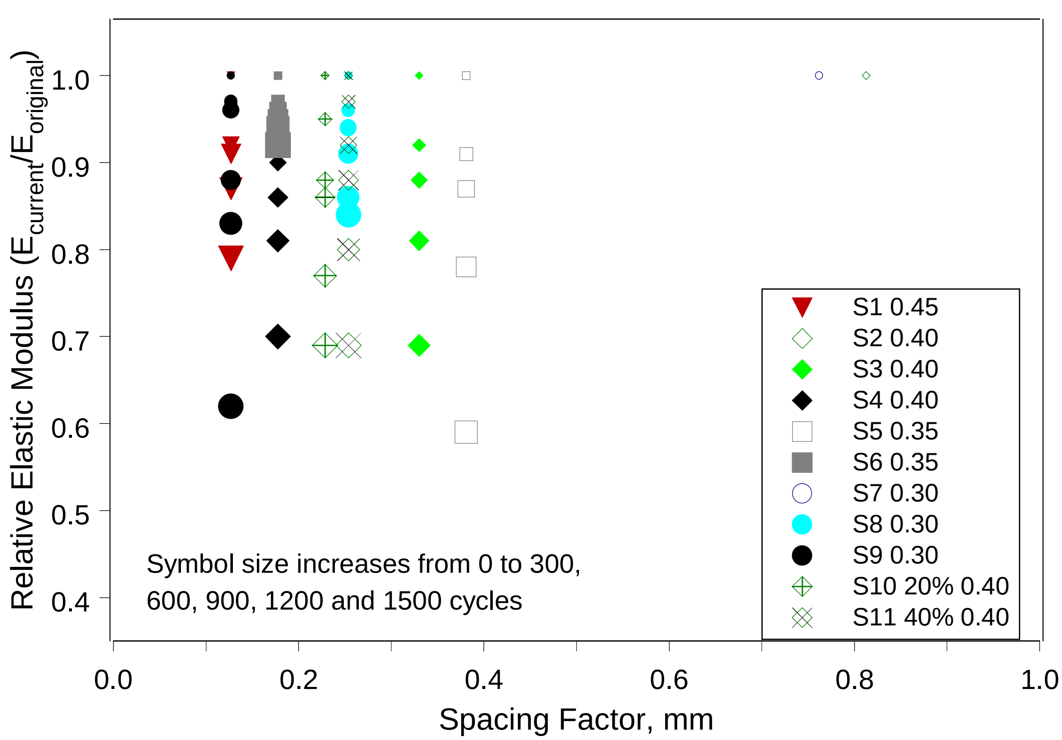

Figure 5. Relative durability of GGBFS mixes based on spacing factor.

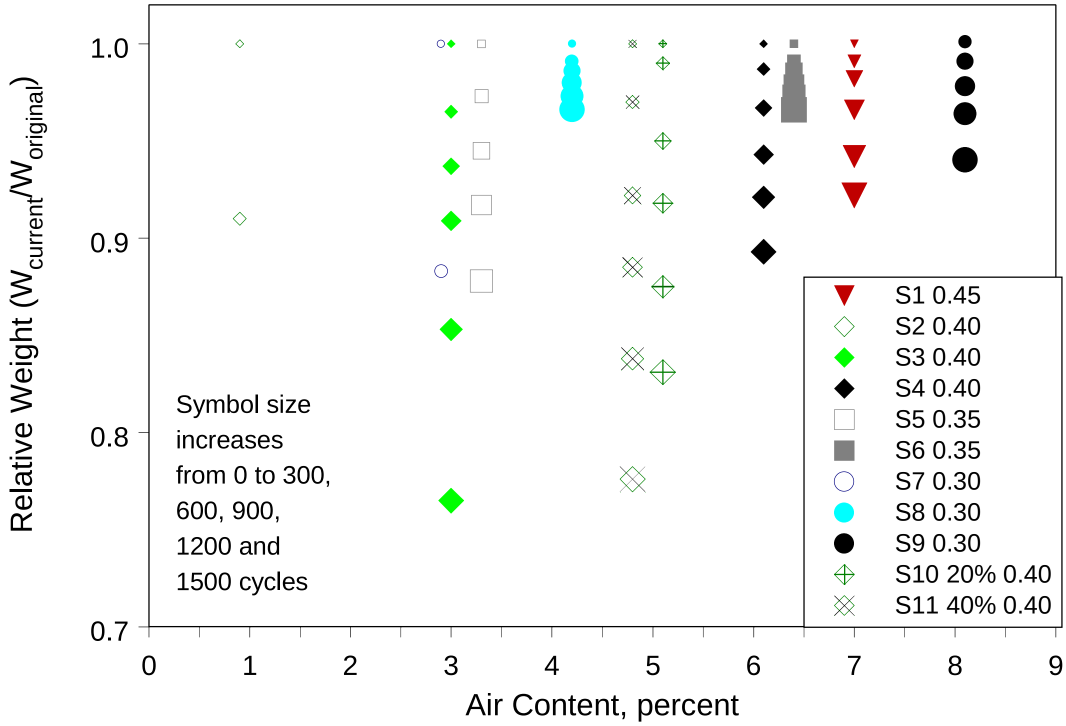

Figure 6. Relative weight loss of GGBFS mixes.

Given the generally strong dependency of relative durability on air content, a method was researched to quantify durability as a function of air content. Such a method could be used as a predictive tool in pavement design. Nonlinear regression led to the identification of Eq. 1 as a predictor of relative durability established from dynamic modulus of elasticity.

$$Durability = 1 - \left(\frac{k}{air\ content} \right)^n \qquad \text{Eq. 1}$$

where: Durability = Relative freeze-thaw durability
k = constant depending on mix characteristics durability level
air content = hardened air content
n = constant ranging from 2 to 3 depending on mix characteristics and durability level. A higher value is used for mix durability that is less sensitive to changes in air content.

Many different equations with various numbers of parameters could have been proposed; Equation 1 was selected based on its relative simplicity and its goodness of fit. Parameters k and n were regressed for durability at 300 cycles and 1500 cycles to capture the extremes of the fly ash series and GGBFS series mixes. Figure 7 shows the proposed equation for the fly ash series and Figure 8 shows the same for GGBFS series of mixes. All mixes are shown for each level of exposure. The equation provides a close fit to data at 300 cycles. More variability results as specimens approach failure at 1500 cycles and as expected the equation fit is not as close.

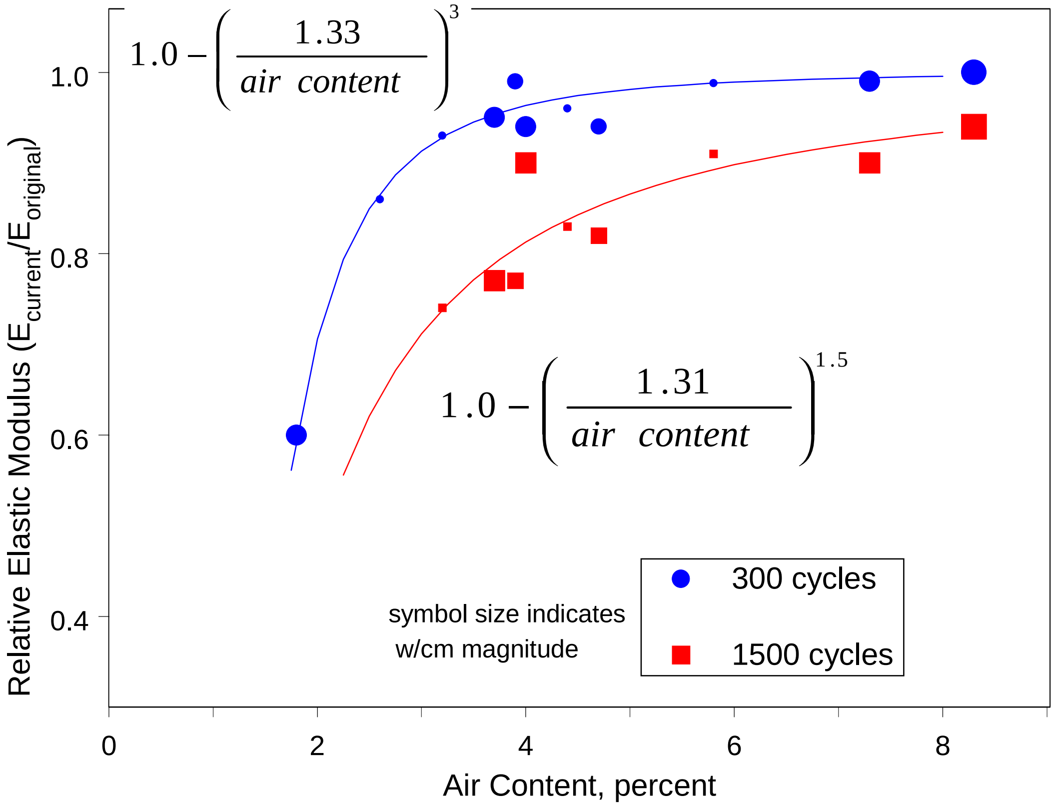

Figure 7. Regression equation fit to fly ash series data.

Relative weight loss is shown in Fig. 9 for the fly ash series and Fig. 10 for the GGBFS series in a form similar to that in Figures 7 and 8. Similar to the relative durability in Figures 7 and 8, the weight loss followed a general trend defined by the air content. At 1500 cycles, the fly ash weight losses were scattered, but this was not the case with GGBFS series. Weight losses decreased as air content increased although the benefit levels off toward 6% air content.

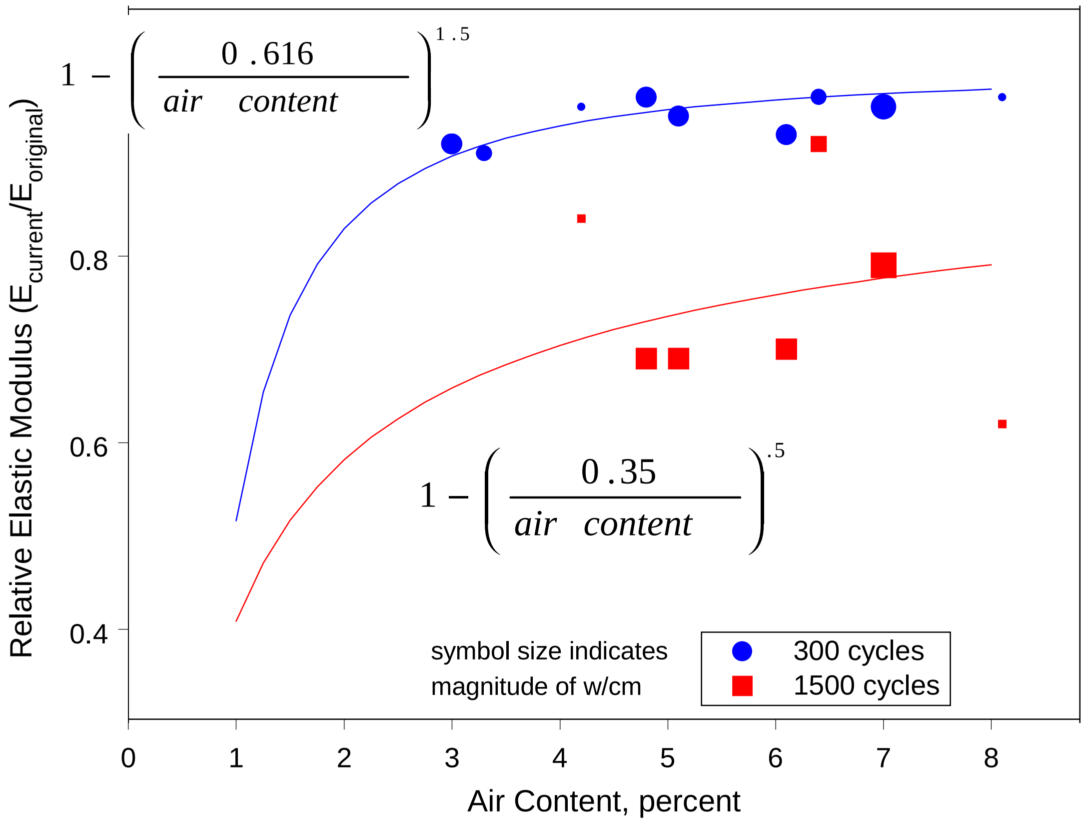

Figure 8. Regression equation fit to GGBFS series data.

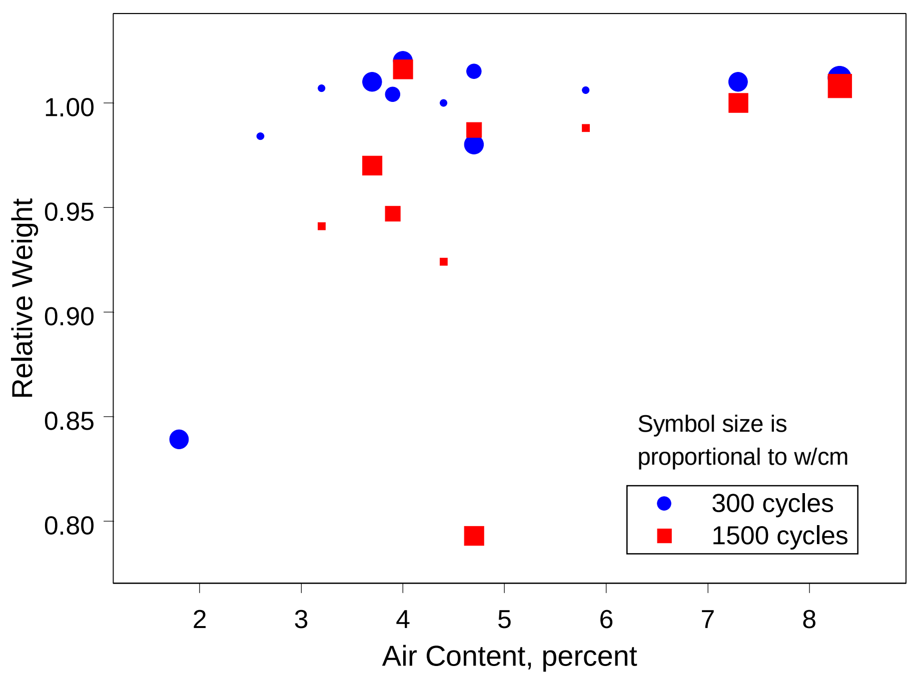

Figure 9. Relative weight vs air content for fly ash series mixes.

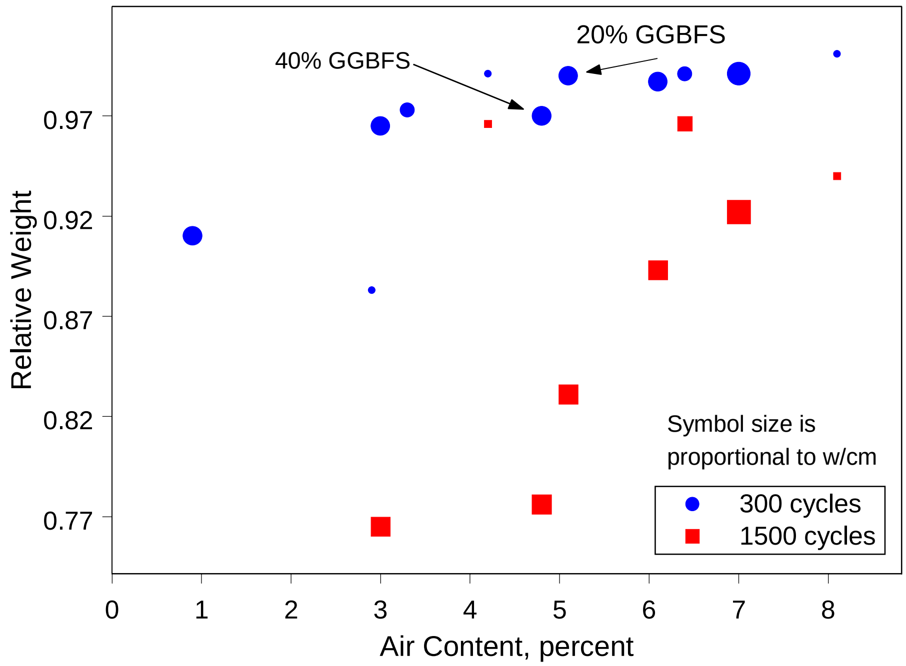

Figure 10. Relative weight vs. air content for the GGBFS series mixes.

5.4 Rapid Chloride Penetrability

Rapid chloride ion penetration (RCP) was measured as a general indication of concrete water permeability as described earlier. Lower permeabilities are believed to contribute to higher concrete durability by limiting the ingress of water into the hardened concrete matrix.

Chloride ion penetration measurements showed inconsistent correlation with durability (Table 5). In the fly ash series, however, chloride ion penetration showed an increasing correlation with weight loss at increasing numbers of cycles, reaching a correlation coefficient of 0.95 and 0.94 at 1200 and 1500 cycles respectively. This positive correlation indicated that higher levels of chloride penetration exhibit higher relative weights suggesting that highly permeable mixes are more durable. This runs opposite to the prevailing theory that low permeability improves concrete durability by limiting the amount of freezable water in the concrete matrix. When the Grade A mix was included in this analysis, high permeability translates to lower durability and increased weight loss. When all data were combined, a meaningful and consistent correlation across all data sets and at all levels of exposure was not established.

Figure 11 shows the RCP test results for the fly ash series and Grade A mixes plotted against w/cm. Larger symbol size indicates higher air contents in Fig. 11. As expected, there is a general trend for chloride ion penetration (permeability) to decrease as w/cm decreases, suggesting that lower w/cm mixes should display greater durability. The addition of 18.6% fly ash in the fly ash series mixes results in a dramatic decrease in chloride ion penetration.

Figure 12 shows a similar plot for the GGBFS series mixes. Several outlier data points present a more confused picture of the relationship between chloride ion penetration and w/cm. Removal of the outlier points, however, results in a trend very similar to that shown for the fly ash series in Fig. 11. One might expect the 50% GGBFS replacement with increased content of ultra fine particles to provide lower chloride ion penetration than the 18.6% fly ash series, but comparison of chloride ion penetration values in Fig. 11 and 12 show general similarity.

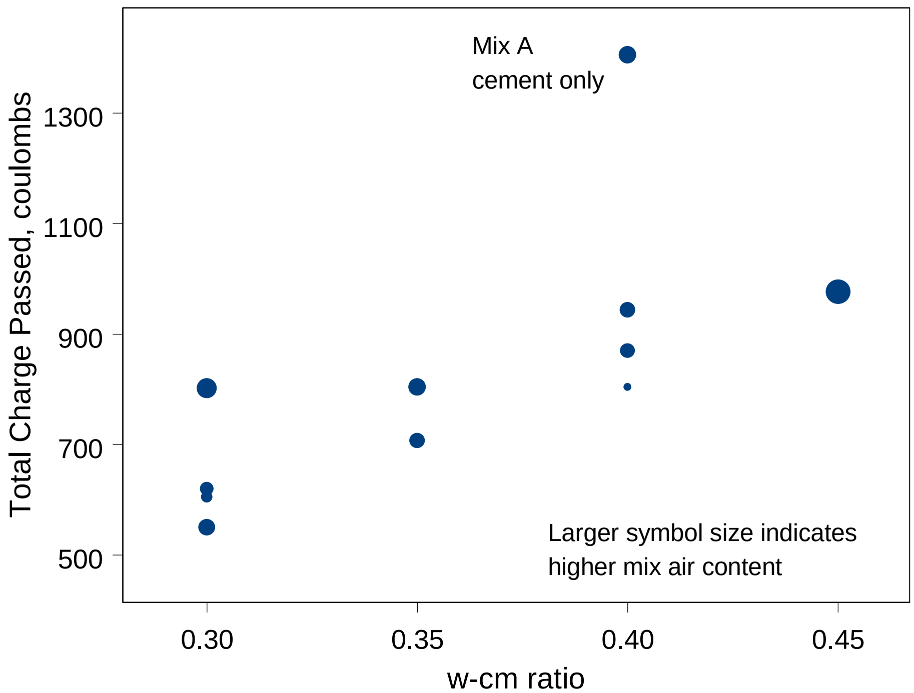

Figure 11. Chloride ion penetration for fly ash and cement mixes versus w/cm.

The question concerning the usefulness of chloride ion penetration results to indicate freeze-thaw durability is addressed in Figures 13 and 14. Figure 13 shows chloride ion penetration plotted against relative durability at 1500 cycles for the fly ash and Grade A mixes. For the fly ash mixes, there is a very clear trend showing higher chloride ion penetrations leading to greater durability. Allowing less restricted water movement in the fly ash series mixes is theorized to provide pressure relieve during the freezing process. The opposite trend is suggested for the GGBFS mixes as shown in Figure 14, but in general the relationship between RCP measurements and durability were mixed. In the GGBFS series lower permeability (as indicated by RCP) tended toward greater durability at 1500 cycles.

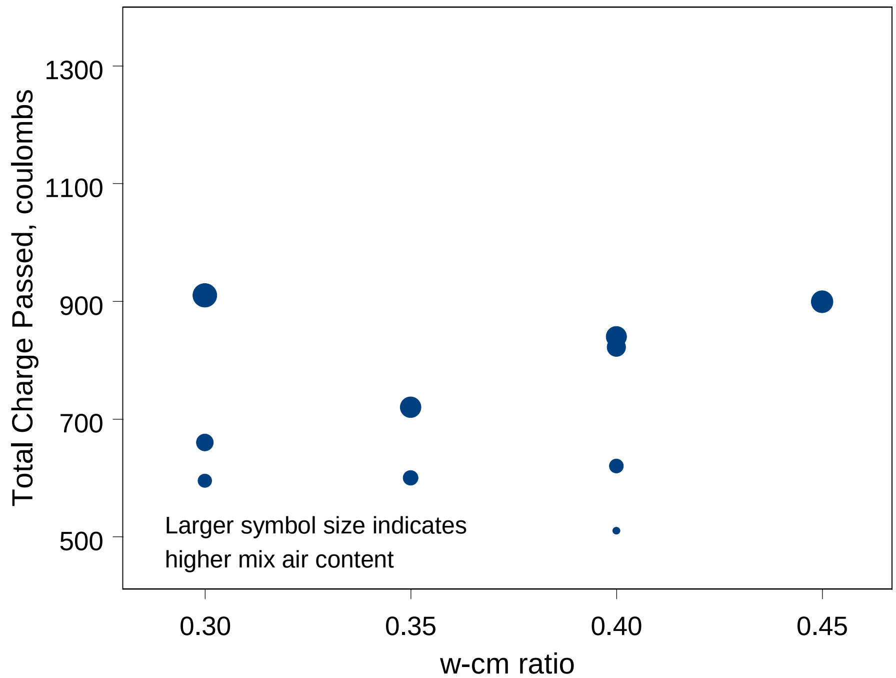

Figure 12. Chloride ion penetration in GGBFS mixes versus w/cm.

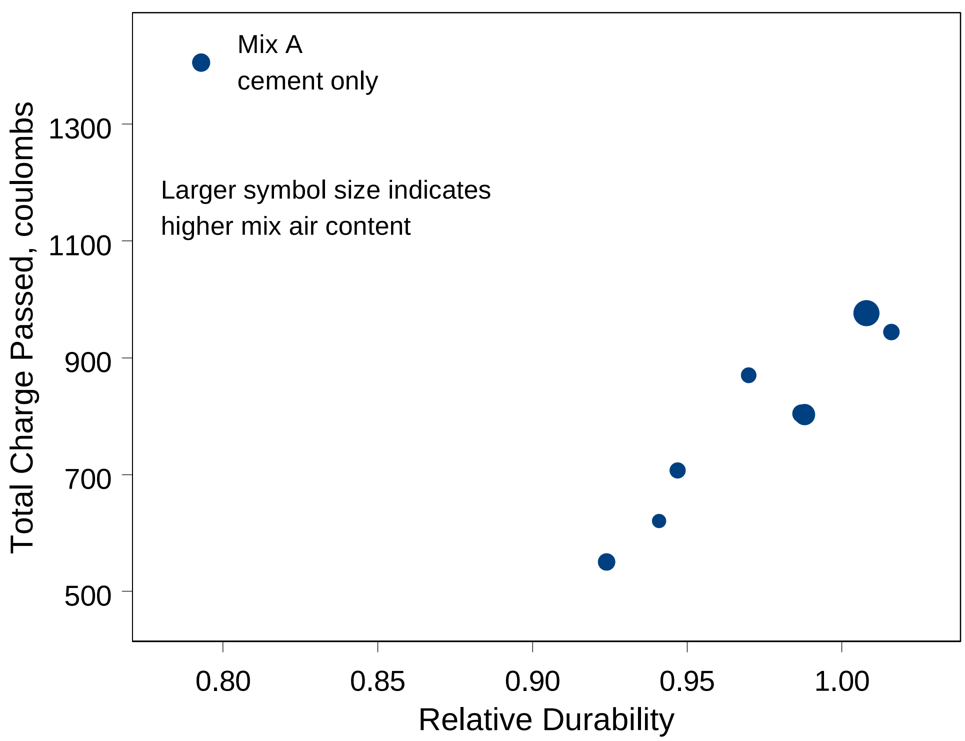

Figure 13. Chloride penetration for fly ash series and Grade A mixes versus relative durability at 1500 cycles.

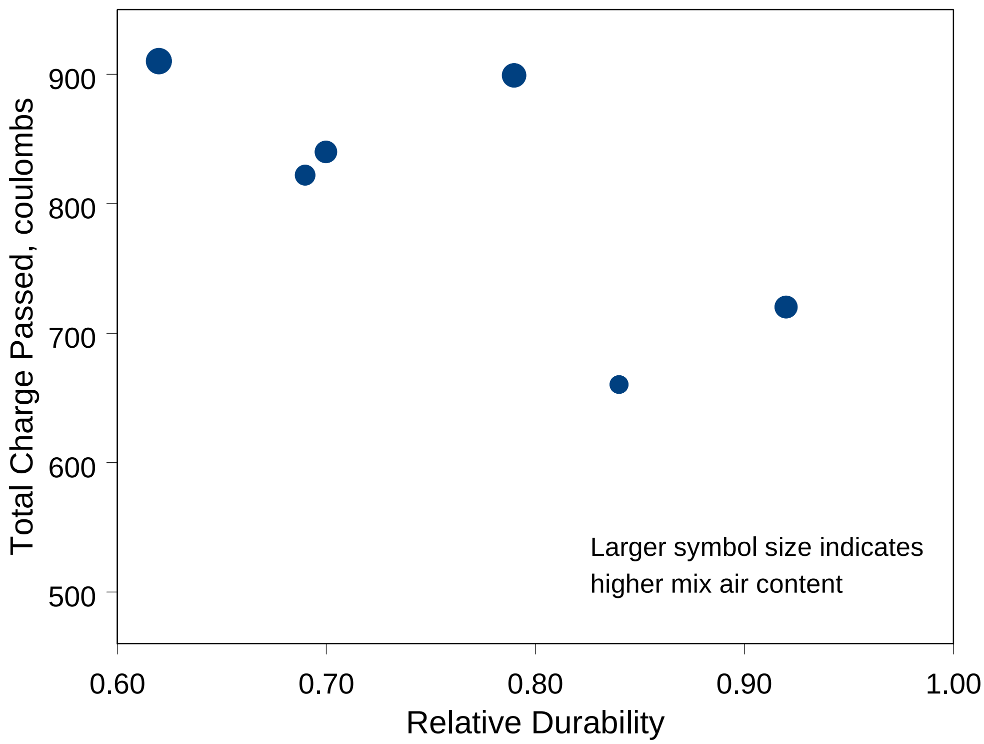

Figure 14. Chloride ion penetration for GGBFS series mixes versus relative durability at 1500 cycles.

5.5 Compressive Strength

Concrete strength forms an important part of the pavement durability picture and is critical to the timing of pavement opening to traffic. Mather[2] has recommended a compressive strength of 27.6 MPa combined with sufficient air content to provide freeze-thaw durable concrete. Compressive strength provides an indirect indicator of the tensile strength necessary to prevent damage due to internal expansion caused by ice during freeze-thaw cycles.

Based on Abrams Law[3], it was expected that as w/cm increases, compressive strength decreases. The general concept was confirmed in Figures 15 and 16 for the fly ash and Grade A mixes, and the GGBFS mixes respectively. These figures show compressive strengths at 3 and 56 days. Both the fly ash mixes and the GGBFS mixes displayed a latent hydration at 3-days which was largely overcome by 56-days. WisDot specifications require a compressive strength of 20.7 MPa for traffic opening.

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[2] Mather, B. Concrete Need Not Deteriorate, *Concrete International*, 1(9), pp. 32-37, 1979.
[3] Abrams, D.A. *Design of Concrete Mixtures*, Bulletin No. 1, Structural Materials Research Laboratory, Lewis Institute, Chicago, IL 1918.

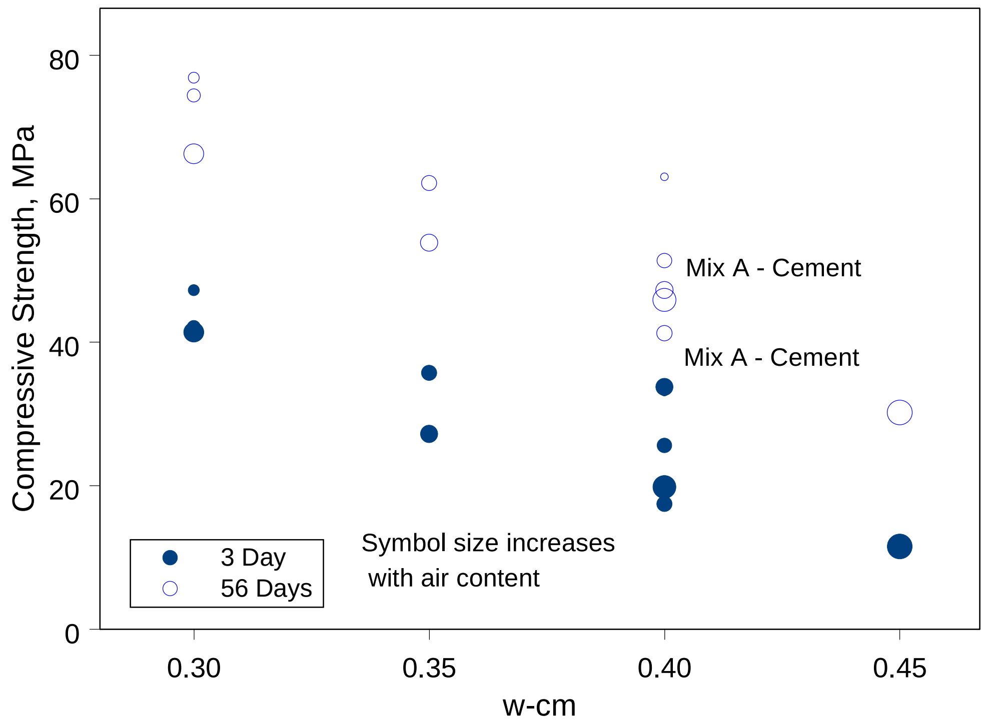

Figure 15. Compressive strength versus w/cm for fly ash series and Grade A mixes at 3 and 56 days.

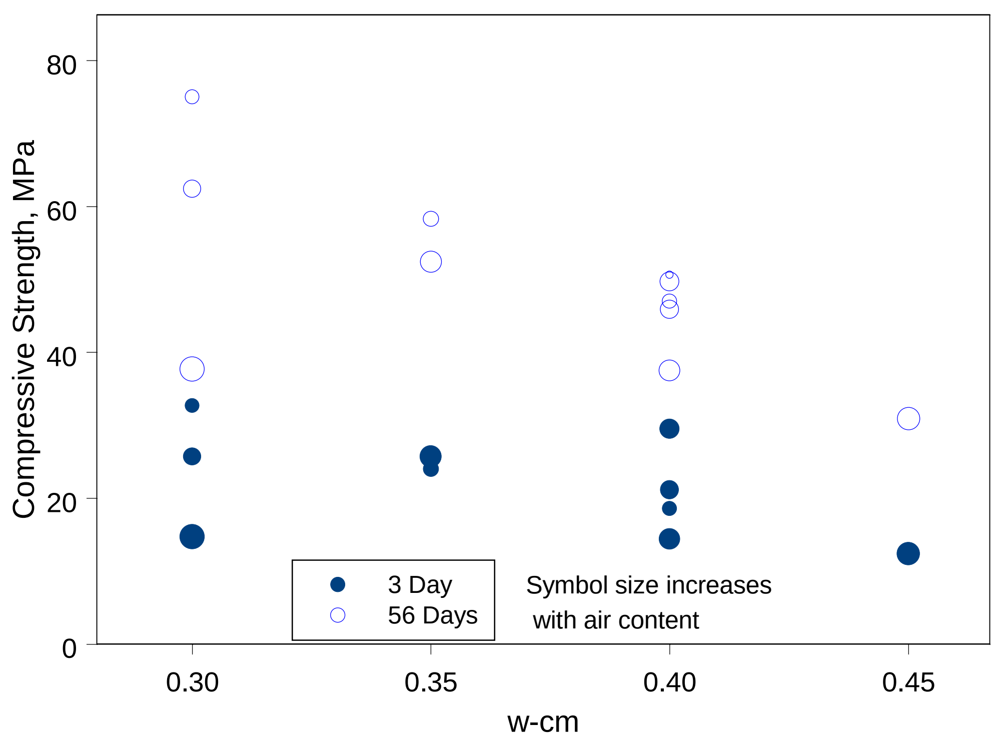

Figure 16. Compressive strength versus w/cm for GGBFS mixes.

Do the higher strength mixes show greater freeze-thaw durability? Figures 17 and 18 show how compressive strength at 56-days related to freeze-thaw durability after 900 cycles of exposure. Similar results were observed at other levels of exposure. As it was shown in Section 5.2 where w/cm had little correlation to freeze-thaw durability, it is not surprising that compressive strength also had little or no direct relation to freeze-thaw durability or at least its influence was masked by air content.

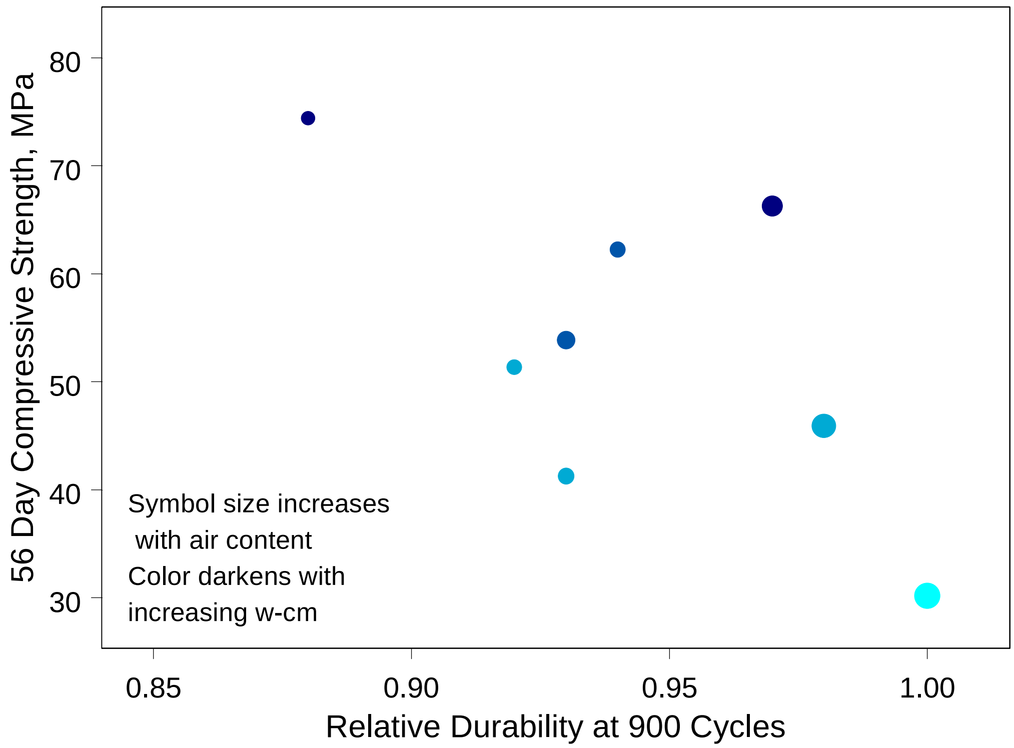

Figure 17. Compressive strength vs. freeze-thaw durability at 900 cycles for fly ash series and Grade A mixes.

The latent hydraulicity imparted by fly ash and GGBFS result in a slow strength development compared to standard Grade A all-portland cement mixes used by the WisDOT. Table 7 compares the compressive strengths at different ages of fly ash and GGBFS series mixes with the compressive strength of the Grade A mix at the same age. Examination of Table 7 reveals the fly ash mixes slightly lag the Grade A during the period from 3 to 28 days unless the w/cm is reduced to 0.3. By 28 days the fly ash mixes have largely achieved strengths that are comparable to the Grade A. Both air content and w/cm have a strong influence in strength development.

The 50% GGBFS mixes (S1-S9) lagged the strength of the Grade A mixes at all ages unless the w/cm ratio was reduced. The 20% GGBFS mix developed strength close to the Grade A and reached equivalency at 28-days. The 40% GGBFS mix was close to strength equivalency at 56-days.

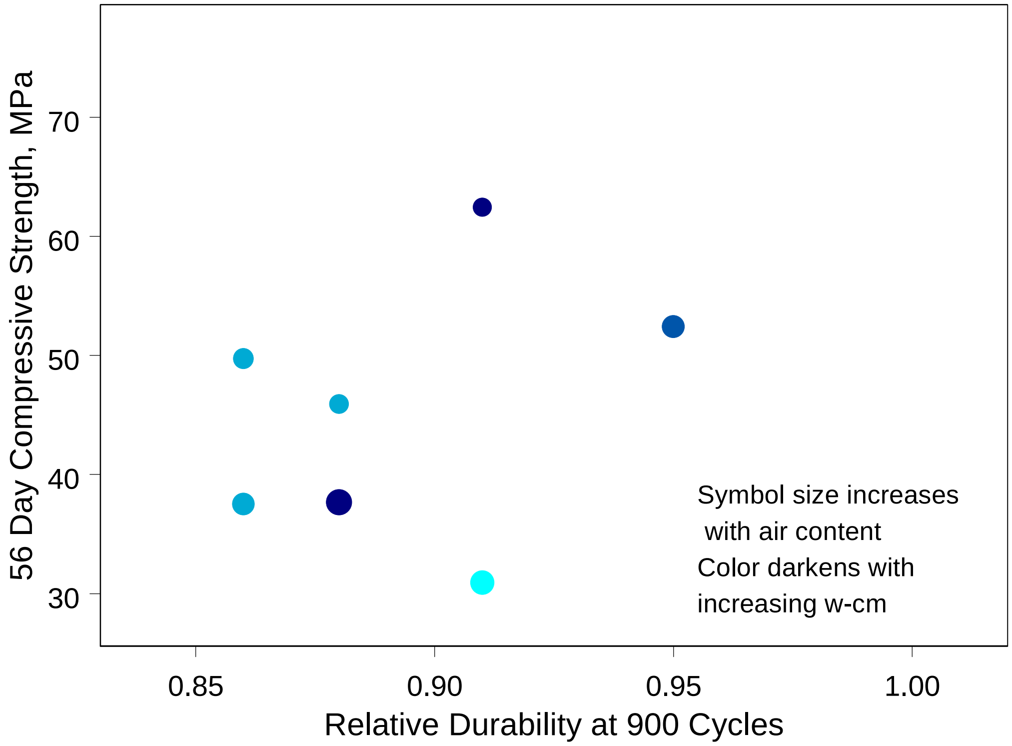

Figure 18. Compressive strength versus freeze-thaw durability at 900 cycles for GGBFS mixes.

5.6 Air Dry Shrinkage

Air dry shrinkage measurements were recorded for specimens representing each fly ash and GGBFS mix as outlined in Section 4.1. Laboratory control problems in temperature and humidity added variability to the results of these tests.

The strongest correlations between shrinkage and durability occurred with relative elastic modulus in the fly ash series. Again however, greater shrinkage correlated with higher durability, opposite prevailing knowledge. Since the correlations were not strong, no conclusions can be established. Because the freeze-thaw specimens were unrestrained, shrinkages did not result in cracking in the same manner that would occur in larger masses of concrete and thus the full detrimental impact of high shrinkage was not fully addressed in the standard test procedure. Figure 19 shows a typical relationship between shrinkage and freeze-thaw durability. Higher shrinkages were associated with the most durable mixes.

Table 7. Relative compressive strengths based on Grade A Mix at 28 days

Mix	w/cm	air content	3-day	7-day	28-day	56-day	365-day
A	0.40	5.0	**100%**	**100%**	**100%**	**100%**	**100%**
FA-1	0.45	8.3	34%	56%	63%	64%	71%
FA-2	0.40	1.8	98%	119%	125%	133%	156%
FA-3	0.40	3.7	76%	93%	103%	109%	103%
FA-4b	0.40	7.3	59%	79%	92%	97%	90%
FA-5	0.35	3.9	106%	116%	121%	132%	131%
FA-6	0.35	4.7	81%	100%	110%	114%	116%
FA-7	0.30	2.6	140%	159%	161%	163%	165%
FA-8	0.30	3.2	125%	145%	152%	157%	142%
FA-9	0.30	5.8	123%	132%	137%	140%	137%
S-1	0.45	7.0	37%	48%	57%	65%	65%
S-2	0.40	0.9	62%	76%	104%	107%	101%
S-3	0.40	3.0	55%	71%	95%	100%	89%
S-4	0.40	6.1	43%	71%	76%	79%	77%
S-5	0.35	3.3	71%	93%	118%	123%	113%
S-6	0.35	6.4	76%	84%	101%	111%	103%
S-7	0.30	2.9	97%	131%	156%	159%	147%
S-8	0.30	4.2	76%	97%	127%	132%	130%
S-9	0.30	8.1	44%	63%	80%	80%	84%
S-10	0.40	5.1	87%	90%	100%	105%	NA
S-11	0.40	4.8	63%	78%	92%	97%	NA

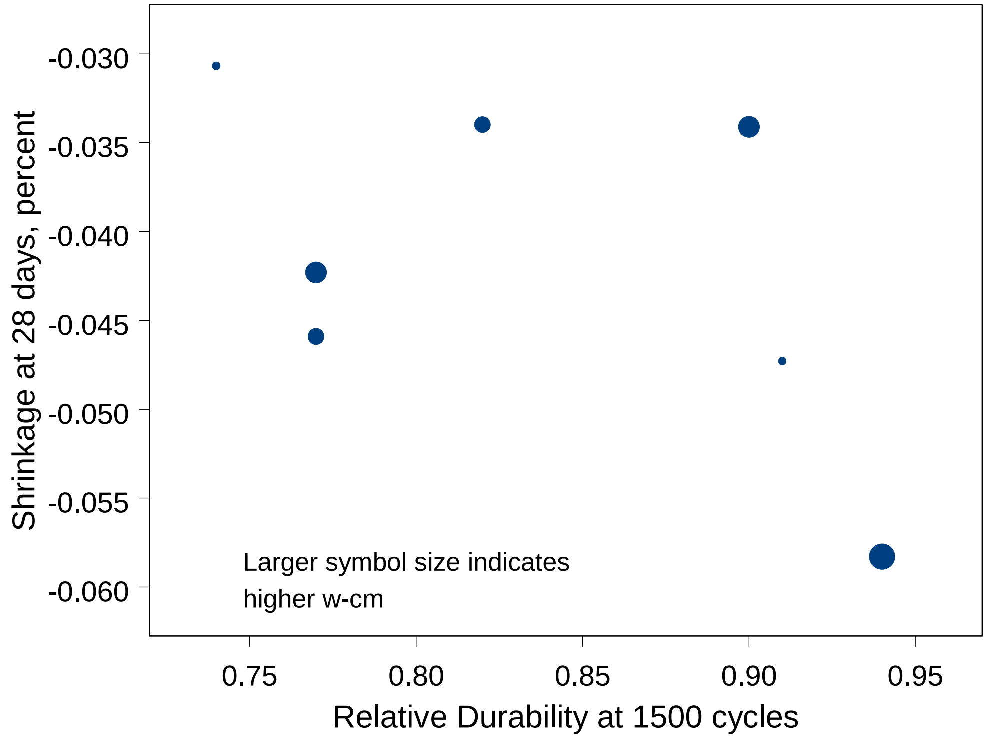

Figure 19. Typical relationship between shrinkage and relative durability (from fly ash series).

5.7 Petrographic Analysis

Petrographic analyses were conducted by a third party on eight specimens from the fly ash series. Four of the specimens were untested specimens from mixes FA-3, FA-6, FA-7 and FA-8 and the remaining four were from specimens subject to freeze-thaw testing. Two cross-sectional thin sections impregnated with blue epoxy were taken from the center region of each concrete prism. The thin sections were then examined using a polarizing microscope at magnifications of 50x, 100x, 200x and 400x. Comparisons were sought between the tested and untested specimens.

The thin sections did not reveal any internal damage or micro cracking in the tested specimens. Freeze-thaw deterioration was limited to surface erosion and scaling suggesting that only the surfaces, saturated with sodium chloride solution, were responsible for the degrade.

Further petrographic analysis was not undertaken given the limited information established.

6. Significance and Theoretical Pavement Life

The evaluations conducted in this research consisted of standard tests established by professional consensus that have been shown to be repeatable and are thus comparable to results from similar tests conducted by others. These tests tend to be indicators of relative performance of mixes for specific properties and do not necessarily translate directly to field performance. For example, the analysis showed higher shrinkage correlated with higher freeze-thaw durability, opposite the expected trend. In this research these properties were measured independently in two separate tests. In the field, shrinkage and freeze-thaw durability occur together. A concrete pavement will exhibit some restraint when shrinkage occurs. Tensile stresses will develop that may lead to cracking and water penetration into these cracks will in turn accelerate freeze-thaw deterioration. Interpretation of the research results must be made with consideration of these interactions that occur in the field.

The ASTM C666 accelerated freeze-thaw test does not correlate one to one with freeze-thaw cycles occurring in the field. Neville[4] and Detwiler et al.[5] discuss how rate of cooling, degree of hydration, and the confined saturation in the ASTM C666 test are more severe than likely to occur in most field circumstances. Detwiler et al. also extends cautions about applying freeze-thaw cycles directly to field exposures.

Despite these concerns, an estimate was made as to the impact on pavement life that the different mix parameters would impart. This estimate was made on the assumption that a standard WisDOT Grade A mix will yield a pavement life of 25 years. It is assumed based on discussions with WisDOT staff that a typical Wisconsin pavement may experience approximately 100 freeze-thaw cycles per year. If we assume that 1500 ASTM C666 Procedure A freeze-thaw cycles are equivalent to a 25 year pavement life for a Grade A mix, this means that 100 annual Wisconsin freeze/thaw cycles are equivalent to 60 ASTM C666 freeze-thaw cycles. This is consistent with the theory that the ASTM C666 cycling is more severe than that in the field. The relative mix performance at 1500 freeze-thaw cycles can be translated into years by proportioning the relative durability measured in this research to the measured durability of the Grade A mix with an assumed life of 25 years. Table 8 summarizes these calculations. Current knowledge is insufficient to evaluate the accuracy of these predictions and many construction variables could alter such predictions. Table 8 again emphasizes the impact of the air void system on freeze/thaw durability with a theoretical estimate of pavement life.

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[4] Neville, A.M. *Properties of Concrete*, 4th Ed. John Wiley and Sons, 1996.
[5] Detwiler, R., Dalgleish, B., and Williamson, R.B. Assessing the Durability of Concrete in Freezing and Thawing, *ACI Materials Journal*, pgs. 29-35, Jan-Feb. 1989.

Table 8. Estimated longevity and life cycle costs for different mixes

Mix Design	w/cm	Hardened air content	Relative durability to Mix A at 1500 cycles	Theoretical pavement life (years)
A	0.40	5.0	1.00	25
FA-2	0.40	1.8	Failed after 300 cycles	5
FA-7	0.30	2.6	Failed after 600 cycles	10
FA-8	0.30	3.2	1.17	29
FA-3	0.40	3.7	1.22	30
FA-5	0.35	3.9	1.22	31
FA-4	0.40	4.0	1.42	36
FA-6	0.35	4.7	1.30	33
FA-9	0.30	5.8	1.44	36
FA-4b	0.40	7.3	1.43	36
FA-1	0.45	8.3	1.49	37
S-2	0.40	0.9	Failed before 300 cycles	3
S-7	0.30	2.9	Failed before 300 cycles	3
S-3	0.40	3.0	Failed after 1200 cycles	20
S-5	0.35	3.3	Failed after 1200 cycles	15
S-8	0.30	4.2	1.33	33
S-11	0.40	4.8	1.10	27
S-10	0.40	5.1	1.10	27
S-4	0.40	6.1	1.11	28
S-6	0.35	6.4	1.46	37
S-1	0.45	7.0	1.25	31
S-9	0.30	8.1	0.98	25

7. Conclusions and Recommendations

7.1 Conclusions

Extended accelerated freeze-thaw testing was completed on specimens primarily from mix designs containing 18.6% fly ash or 50% GGBFS. The conclusions from this study are itemized below:

- The test results confirmed that freeze-thaw durability overwhelmingly depends on the adequacy of the air void system. The data trends can be used through equations that are a function of only air content to predict concrete durability.
- The durability of GGBFS mix designs were not as dependent on air content as the fly ash series mix designs as the number of freeze/thaw cycles approached 1500. The durability of GGBFS appears to be influenced by other mechanisms that were not fully revealed in this research.
- A minimum air content of 4% with a spacing factor of not more than 0.4 mm was necessary to avoid rapid freeze-thaw failure.

- There was consistent improvement in the durability of the fly ash series specimens as air contents increased to and exceeded 8% and spacing factors approached 0.10 mm. This trend was also present in the GGBFS mixes up to 1200 cycles, but the benefits became less clear as the specimens degraded from 1200 to 1500 cycles.
- Laboratory prepared 50% GGBFS mix designs with air contents of 4% or higher showed adequate durability but scaling and the resulting weight losses were higher than fly ash series mixes.
- Decreases in water-cementitious material ratio do not compensate in durability for reductions in air content. The relatively high water cementitious material ratio mixes had durabilities that were comparable and, in some cases, better than low water cementitious material ratio mixes.
- Fly ash mixes were significantly more durable than comparable Grade A mixes.
- 50% GGBFS mixes had durability that was comparable to Grade A mixes.
- Chloride ion penetration as an indicator of permeability suggested that higher permeabilities in the fly ash series were more durable. In the GGBFS series, the relationship between chloride ion penetration and durability was inconclusive.
- Compressive strength was related to w/cm as expected with increased compressive strength and rate of strength gain related to lower w/cm. The relationship was stronger for the fly ash mixes as compared to the GGBFS mixes.
- Concrete compressive strength showed no meaningful correlation with freeze-thaw durability.
- Traffic opening delays for new concrete pavement will be greater and perhaps unacceptable using 50% GGBFS mix designs even with a w/cm of 0.40.
- Air-dry shrinkage measured independently of freeze/thaw durability was only weakly related to durability with higher shrinkages associated with the most durable specimens. This weak association is perhaps an artifact of the test procedures and is not a basis for targeting future durability improvements.

The performance measurements in this study (strength, shrinkage, permeability, freeze-thaw durability) were measured independently. Interpretation of the relationships and correlations amongst these parameters should consider the interactions in these parameters that can occur in the field.

7.2 Recommendations

Results of this research have implementation impacts for both the near term and the long term. Key recommendations are as follows:

- From the combined concern of rate of strength gain and freeze/thaw durability, mix designs with w/cm of 0.4 and an air content of 6% represent an optimal mix design. Concretes with 8% air content showed slightly higher durability, but also showed significantly reduced compressive strengths. The trade off between strength development and durability must be considered in choosing a target air content.
- The WisDOT A-FA mix design provides the highest level of freeze/thaw durability.
- From a strength development viewpoint, the 50% GGBFS mix design provides little margin for error when air content and w/cm fluctuate. A lower replacement level should be investigated.
- The durability of the 50% GGBFS concrete while in some cases excellent, was generally less predictable. Development of the factors that differentiate the highly durable GGBFS mixes from the less durable is needed.
- Air void systems in paving concrete are critical to longevity of the pavements. New efforts to ensure that adequate air void systems are produced and new research to better understand the parameters that contribute to adequate development of air void systems are recommended.
- Concrete durability and longevity depend on interrelationships between shrinkage, strength and freeze/thaw deterioration. Current standard test procedures do not allow these interrelationships

to be analyzed. Future research that more realistically tests durability with the interrelationships present is recommended and will lead to new insights and construction guidelines for durable concrete pavements.

8. Acknowledgements

The authors gratefully acknowledge the financial support of this research from the Wisconsin Department of Transportation. The contributions of graduate students C. Santos, J. Drozdek and A. Carpenter to various aspects of the project were key to successful completion. The material contributions from Holnam, Inc. LaFarge Corp., WR Grace & Co., Yahara Materials and Wingra Redimix are appreciated. We are grateful for the on-going support of the Wisconsin Concrete Pavement Association and its member companies, and the Midwest Cement Shippers.

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APPENDIX II – Synthesis of Bibliography

The freeze-thaw durability of concrete should be evaluated by two distinct processes of deterioration: **paste damage (PD)**--surface scaling and weight loss, and **concrete damage (CD)**--internal cracking which leads to failure by a decline in the relative elastic modulus (Li et al. 1994). Internal cracking does not always accompany severe scaling (Carrasquillo, 1987 and Johnston, 1987).

Durability assessed by:
PD= weight loss CD= % relative E

PERMEABILITY

It is well documented that reduced permeability does not necessarily lead to increased FT resistance:

REFERENCES	CD[i]	PD
• Bowser et al, 1996	X	
• Zia and Hansen, 1993	X	
• Johnston, 1995		X
• Geisler et al, 1995		X
• Tikalsky et al, 1989	X	
• Koch Minerals Co, 1993	X	X

WATER-CEMENT

CONCEPT	REFERENCES	CD	PD
1. Increasing the cement content *increases* the freeze-thaw resistance to scaling **(PD)**.	• Ghafoori and Mathis, 1994 • Ghafoori and Mathis, 1997 (600 lb/cu. yd.) • Ghafoori and Mathis, 1995		X X X
2. Increasing the cement content ***increases*** the freeze-thaw resistance to concrete damage **(CD)**.*Conflicts with #3	• Concrete for Railways (PCA)	X	
3. Increasing the cement content ***decreases*** the freeze-thaw resistance to concrete damage **(CD)**. *Conflicts with #2	• Bowser et al,1996	X	
4. A lower aggregate-cement ratio (3:1) *increases* the freeze-thaw resistance to scaling.	• Ghafoori and Mathis, 1995		X
5. High strength concrete (w/c =.30; cement, fly ash, silica fume = 500kg/cu. m) is more freeze-thaw durable (CD) than normal strength concrete (w/c = .45; cement = 350kg/cu. m).	• Marzouk and Jiang, 1994	X	
6. Increasing the w/c *increases* scaling, even when silica fume is used.	• Johnston, 1995		X

[i] NA = not applicable, ND = not discussed, ILL= abstract only; reference is being obtained through interlibrary loan

AIR-ENTRAINMENT

CONCEPT	REFERENCES	CD	PD
7. The air void spacing factor should be less than 400 μ.	• Pigeon et al,1995 • NCHRP,1996 • Khayat, 1995 (w/c .45, .49) • Pigeon et al, 1987 (w/c .3) • Saucier et al, 1991 (200μ) • ASTM C457 (200 μ)	 X X X NA NA	X X
8. In freezing and thawing tests, non-air-entrained concretes incorporating pozzolans showed poorer results than ordinary portland cement. When air-entrained, concretes with pozzolans showed better freeze-thaw resistance than ordinary portland cement.	• Malhotra and Mehta, 1996	ND	
9. The impact of placing method on air content and air-void system had negligible effects on freeze-thaw durability. The specimen (w/c .45) experiencing the greatest loss of air content (3.4% Vs 5.8%) as a result of pumping had the highest durability (102% Vs 97%).	• Hover and Phares, 1996	X	
10. Concrete with a low/mod w/c **requires** air-entrainment for freeze-thaw protection. *Conflicts with #11	• Miura and Itabashi, 1995 • Cohen et al, 1992 (w/c .35) • Malhotra et al,1987 (w/c .25-.35) • Malhotra, 1982 (w/c >.35) • Malhotra, 1986 (w/c .4-.6) • NCHRP #208	X X X X X X	X X X X
11. Concrete with a low w/c **does not require** air-entrainment for freeze-thaw protection. *Conflicts with #10	• Luther and Hansen, 1989 (w/c .29, .38) • Malhotra, 1982 (w/c .35) • Yamato et al, 1986 (w/c .25, .35) • Pigeon and Marchand, 1996 (w/c .25) • Kashi and Weyers, 1989 (w/c .32) • Folliard, 1995 (w/c .25) • Li et al, 1994 (w/c < .27) • Kukko and Matala, 1991 (w/c <.30, comp strength >80 Mpa) • Pigeon et al, 1991 (w/c .26)	X X X ND X X X X X	X X X X X

AGGREGATES

CONCEPT	REFERENCES	CD	PD
12. Crushed igneous granite aggregate outperforms natural sedimentary limestone aggregate in air-entrained concrete (>4%).	• Zia and Hansen, 1993 • OPT GRAD II PROJECT	X X	
13. Crushed sedimentary limestone aggregate outperforms igneous crushed diabase aggregate.	• Folliard, 1995	X	
14. The moisture content of aggregate plays a key role in freeze-thaw resistance. The onset of freeze-thaw deterioration began when limestone aggregate had been saturated 80-95%.	• Lane and Meininger, 1987	X	X
15. A small percentage of chert and other deleterious or lightweight particles included in the coarse aggregate had a large negative effect on freeze-thaw resistance.	• Sawan, 1987	ND	
16. Drying a coarse aggregate before mixing in the concrete, or allowing the concrete to dry before freezing improves the durability of concrete.	• Sawan, 1987	ND	
17. Increasing the maximum size of the coarse aggregate decreases freeze-thaw resistance.	• Sawan, 1987	ND	
18. Only sedimentary or poorly metamorphized sedimentary rocks cause D-cracking. D-cracking is caused by freeze-thaw action on coarse aggregate.	• Sawan, 1987	ND	
19. Surface treatments, subsurface treatments, or drainage systems were not effective in impeding the progress of D-cracking.	• Sawan, 1987	ND	
20. The resistance of concrete to the freezing cycles is dependent on the mineralogical structure and physical-chemical properties of the aggregate, its granulometric composition, and the bond between the cement paste and the aggregate. If the aggregate is not adequate in the above, neither cement quality or increasing the amount of cement nor the air-entrainment can prevent destruction by freeze-thaw.	• Teodoru, 1987	X	
21. A volume blending ratio of slag fine aggregate in excess of 60% resulted in poor freeze-thaw resistance (w/c .55, air <5%)--attributed to bleeding.	• Shoya et al, 1994	ILL	

SUPERPLASTICIZER

CONCEPT	REFERENCES	CD	PD
22. The addition of air-entrainment after a viscosity modifying admixture ensures smaller air bubbles and spacing factors.	• Khayat, 1995		X
23. The air-void spacing factor is not affected by the presence of a superplasticizer. **Robson, 1987**: Additions of HRWR increase the bubble size.	• Pigeon and Marcel, 1991 • Robson, 1987	NA X	 X

24. Freeze-thaw durability of air-entrained concrete with HRWR proved inferior to air-entrained concretes without HRWR when tested using the same procedure.	• Robson, 1987	X	X
25. The durability factors of concretes containing superplasticizer and at least a small volume of air (2.9%) were not influenced by slump or superplasticizer dosage.	• Gagne et al, 1996 • Folliard, 1995 • Baalbaki and Aitcin, 1994	X X X	X

SLAG CEMENT

CONCEPT	REFERENCES	CD	PD	Cured (days)
26. For **non-air-entrained** concrete: granulated blast furnace slag cement replacement ***does not increase*** the freeze-thaw resistance to scaling **(PD)**.	• Madej et al, 1995 (high strength mortars with 40% gbfs) • Geisler et al, 1995 (w/c .45) 42% gbfs ~ 0% gbfs	X	X X	7, 28, 90 28
27. For **air-entrained** concrete (w/c ~.4): granulated blast furnace slag cement replacement ***does not increase*** the freeze-thaw resistance to scaling **(PD)**. *Conflicts with #28	• Afrani and Rogers, 1994 (25% gbfs = 0% gbfs = great dur; 50% gbfs = poor dur) • Malhotra and Mehta, 1996		X X	14-28 ND
28. For **air-entrained** concrete: ggbfs cement replacement ***does increase*** the freeze-thaw resistance to scaling. Concrete with 20-35% ggbfs cement showed greater resistance to scaling than ordinary portland cement concrete. *Conflicts with #27	• Koch Minerals Co, 1993	X	X	ILL
29. For **non-air-entrained** concrete: the salt scaling resistance of concretes rich (>60%) in gbfs *cannot* be improved by air-entraining agents in the same way comparable portland cement concrete can, even if spacing factors are ideal.	• Stark and Ludwig, 1997		X	28
30. For **air-entrained** concrete: ggbfs cement replacement ***does not increase*** the freeze-thaw resistance to concrete damage (CD).	• Koch Minerals Co, 1993 • Madej et al, 1995 (high strength mortars with 40% gbfs) • Malhotra and Mehta, 1996	X X X	X X	ILL 7, 28, 90 ND
31. Ggbfs reduces the permeability of concrete.	• Roy et al., 1986 • Ozyildirim, 1994 (additions of slag are more effective in reducing permeability than by lowering the w/c in concretes not containing these ingredients)	NA NA		7, 28 28
32. The chloride permeability of air-	• Saito et al, 1994	NA		28

entrained admixture free concrete containing ggbfs cement remains almost constant with repeated freeze-thaw cycles when the air-content increases to 3.4%.				
33. To reduce initial scaling of ggbfs concrete, slow down the speed of carbonization by adding CaOH2 or Zemdrain (formwork), curing better, and using a low w/c.	• Stark and Ludwig,1997 • Stark and Ludwig,1995		X X	28 ND
34. The use of an activated ggbfs cement *decreased* PD and CD resistance. Sodium silicate activated gbfs produced marginally less freeze-thaw resistance than ordinary portland cement concrete, but sodium carbonate drastically reduced freeze-thaw resistance.	• Gifford and Gillott, 1996	X	X	ND

FLY ASH CEMENT

CONCEPT	REFERENCES	CD	PD	Cured (days)
35. Fly ash bearing concretes show relatively low chloride permeability with repeated freeze-thaw cycles when the air-content is increased to 5.3%.	• Saito et al, 1994	NA		~28
36. Fly ash lowers permeability.	• Ozyildirim, 1994 • Saricimen et al, 1992 (irrespective of curing procedure compared to comparable ordinary portland cement concrete) • Swamy and Laiw, 1995	NA NA NA		28 28
37. Air-entrained concrete with fly ash scales much more than similar concrete without fly ash—both have similar freeze-thaw resistance with respect to CD however.	• Bilodeau et al, 1994 • Sajadi, 1987 • Klieger and Gebler, 1987 • Carrasquillo, 1987	X X X	X X X X	14 ILL variable 14
38. At 180 days and 365 days, there were unreacted class f fly ash particles in large proportions of the paste (w/c .3).	• Zhang, 1995 • Berry et al, 1994	NA NA		Aged 365 Aged 180
39. At 180 days, of the four cements tested--ordinary portland cement, natural pozzolan, class c fly ash, and class f fly ash--the natural pozzolan and the class f fly ash pastes had the lowest CaOH2 contents.	• Vagelis et al, 1992	NA		Aged 180
40. There is considerably less pore water in ordinary portland cement pastes than in fly ash pastes even at 180 days.	• Berry et al, 1994	NA		Aged 180
41. Fly ash reduces the corrosion rate of	• Ellis, 1992	NA		ND

reinforcing steel.				
42. Concrete with 15% class c fly ash shows more filling of ettringite in entrained air voids, and has greater freeze-thaw expansion when compared with similar mixes without fly ash.	• Ouyang and Lane, 1996		X	>59
43. Concrete with 20-35% fly ash were as freeze-thaw durable (CD) as ordinary portland cement concrete after 300 cycles (4.5-5.5% air). ***Specimens with Type IP cement (20% fly ash and **2.5%** air) also were undamaged—**low air!**	• Tikalsky et al, 1987	X		ND
44. Concretes with fly ash are more sensitive (permeability) to poor curing.	• Saricimen et al, 1995 • Thomas and Matthews, 1994	NA NA		Variable Variable

RICE HULL ASH CEMENT

CONCEPT	REFERENCES	CD	PD	Cured (days)
45. Concrete with a low w/c (.25) and superplacticizer is as freeze-thaw durable (CD) as concrete with rice hull ash.	• Folliard, 1995	X		ILL
46. The durability factor and scaling resistance of 10% rice hull ash concrete (5.1% air, w/c .4) is the same as ordinary portland cement concrete (5.8% air, w/c .4) after 300 cycles.	• Zhang and Malhotra, 1996	X	X	28
47. Rice hull ash concrete lowers permeability.	• Zhang and Malhotra, 1996	X	X	28

UNCONVENTIONAL METHODS FOR ENHANCING FREEZE-THAW DURABILITY

CONCEPT	REFERENCES	CD	PD
48. <u>Self-Cure Concrete</u>: A water-soluble polymeric glycol (self-cure) reduced initial surface absorption, chloride permeability, carbonation, corrosion potential and length-change and scaling associated with repeated freeze-thaw cycles. The improvement is dependent on the dosage. Self-cure inhibits the growth of CaOH2. At higher dosages, strength is compromised.	• Dhir et al, 1995 • Dhir et al, 1996		X X
49. <u>Non-Air-Entraining Polymer Dispersion</u>: The weight loss of concrete in 3% NaCl solution containing the non-air-entraining polymer dispersion was zero after repeated freeze-thaw cycles. This contradicts the	• Aavik and Chandra, 1995		X

air-entrainment theory for enhancing freeze-thaw durability. This polymer reduces the amount of CaOH2 and minimizes its crystal size. It outperformed conventional air-entraining agents in the prevention of weight loss.			
50. <u>Belite Cement</u>: Since belite cements are lower in C3S, they produce less CaOH2 crystals which are believed to be a primary contributor to decreased freeze-thaw resistance. Reactive belite cements have shown better strength developments, lower depth of carbonation, and higher impermeability with respect to a non-activated belite cement and a commercial alitic cement.	• Muller et al, 1995 • Chatterjee, 1996	ND ND	
51. <u>Micro-Fibers</u>: At high air contents, steel fiber reinforced concrete exhibits slightly better freeze-thaw durability (CD) than plain concrete. At lower air contents, however, reinforced specimens show freeze-thaw durability characteristics that are comparable to those of plain specimens.	• Soroushian et al, 1992	X	
52. <u>Micro-Fibers</u>: Microfibers reduce the rate of deterioration due to freeze-thaw but do not completely prevent damage.	• Pigeon et al, 1996		X
53. <u>Alkaline Earth Silicate</u>: Reduces chloride permeability.	• Miller and Fielding, 1997	NA	

CURING REGIMEN

CONCEPT	REFERENCES	CD	PD
54. Increasing the duration of curing in saturated lime water from 7 days to 14, 21, and 56 prior to freeze-thaw testing using ASTM C666 did not influence freeze-thaw durability for air-entrained concrete (w/c .35)	• Cohen et al, 1991	X	
55. Non-air-entrained concrete (w/c .24) remained in excellent condition after 1000 freeze-thaw cycles regardless of the curing age (14, 28, and 90 days).	• Li et al, 1994	X	X
56. Non-air-entrained concrete (w/c .26-.3) cured at 1, 3, 7 and 3, 7, 28 days had similar dynamic moduli. At w/c .26, concrete was freeze-thaw resistant regardless of curing length (3, 7, 28 days).	• Pigeon et al, 1991	X	
57. For air-entrained concrete, a comparatively short curing period is sufficient to obtain high durability. Prolonged storage in water may reduce durability. Optimum duration is 3-7 days.	• Gunter et al, 1997		X
58. Non-air-entrained high-strength concrete (w/c <.30) is freeze-thaw resistant regardless of curing time (14 and 28 days).	• Kashi and Weyers, 1989	ILL	

Appendix III – Chemical Composition of Cementitious Materials (% by weight)

Oxide	Portland Cement	Class C Fly Ash	Grade 100 GGBFS
SiO_2	20.7	32.5	37.8
Al_2O_3	4.7	18.9	8.1
MgO	1.9	4.7	10.7
CaO	64.9	27.4	39.3
Fe_2O_3	3.0	6.1	0.5
SO_3	2.5	3.1	2.0
Na_2O	0.1	1.9	0.3
K_2O	0.55	0.4	0.4
TiO_2	Na	1.3	0.5
P_2O_5	Na	1.5	<.01
Mn_2O_3	Na	0.1	.1
SrO	Na	0.5	.1
L.O.I.	1.2	0.5	Na
Alkalis as Na_2O	0.5	2.2	0.52

Appendix IV - Freeze-Thaw Data Summary

Relative Elastic Modulus Data

Mix	300 cycles	600 cycles	900 cycles	1200 cycles	1500 cycles
A	0.94	0.88	0.77	0.73	0.63
FA-1	1.00	1.00	1.00	0.98	0.94
FA-2	0.60	failed			
FA-3	0.95	0.94	0.92	0.86	0.77
FA-4	0.94	0.95	0.93	0.92	0.90
FA-4b	0.99	0.99	0.98	0.96	0.90
FA-5	0.99	0.98	0.94	0.87	0.77
FA-6	0.94	0.94	0.93	0.88	0.82
FA-7	0.86	0.70	failed		
FA-8	0.93	0.92	0.88	0.83	0.74
FA-8b	0.96	0.94	0.92	0.88	0.83
FA-9	0.99	0.99	0.97	0.95	0.91
S-1	0.96	0.92	0.91	0.87	0.79
S-2	failed				
S-3	0.92	0.88	0.81	0.69	failed
S-4	0.93	0.90	0.86	0.81	0.70
S-5	0.91	0.87	0.78	0.59	failed
S-6	0.97	0.96	0.95	0.94	0.92
S-7	failed				
S-8	0.96	0.94	0.91	0.86	0.84
S-9	0.97	0.96	0.88	0.83	0.62
S-10	0.95	0.88	0.86	0.77	0.69
S-11	0.97	0.92	0.88	0.80	0.69

Relative Weight Data Summary

Mix	300 cycles	600 cycles	900 cycles	1200 cycles	1500 cycles
A	0.98	0.94	0.90	0.85	0.79
FA-1	1.01	1.01	1.01	1.01	1.01
FA-2	0.84	failed			
FA-3	1.01	1.01	1.00	0.99	0.97
FA-4	1.02	1.02	1.02	1.02	1.02
FA-4b	1.01	1.01	1.01	1.00	1.00
FA-5	1.00	0.99	0.98	0.96	0.95
FA-6	1.02	1.01	1.01	1.00	0.99
FA-7	0.98	0.92	failed		
FA-8	1.01	1.00	0.99	0.96	0.94
FA-8b	1.00	0.98	0.96	0.94	0.92
FA-9	1.01	1.00	1.00	0.99	0.99
S-1	0.99	0.98	0.97	0.94	0.92
S-2	0.91	failed			
S-3	0.97	0.94	0.91	0.85	0.76
S-4	0.99	0.97	0.94	0.92	0.89
S-5	0.97	0.95	0.92	0.88	failed
S-6	0.99	0.99	0.98	0.97	0.97
S-7	0.88	failed			
S-8	0.99	0.99	0.98	0.97	0.97
S-9	1.00	0.99	0.98	0.96	0.94
S-10	0.99	0.95	0.92	0.88	0.83
S-11	0.97	0.92	0.89	0.84	0.78

Appendix V – Rapid Chloride Ion Penetration Data Measured after 265 Days of Wet Curing

Mix	RCP, Coulombs
FA-1	976
FA-2	804
FA-3	870
FA-4	944
FA-4b	Not gathered
FA-5	707
FA-6	804
FA-7	605
FA-8	620
FA-8b	550
FA-9	802
S-1	899
S-2	510
S-3	620
S-4	840
S-5	600
S-6	720
S-7	595
S-8	660
S-9	910
S-10	822
S-11	Not gathered

Appendix VI – Compressive Strength Data Summary

			Compressive Strength, MPa				
Mix	**w-cm**	**air**	**3-day**	**7-day**	**28-day**	**56-day**	**365-day**
A	0.40	5.0	33.74	38.87	45.09	47.25	54.94
FA-1	0.45	8.3	11.51	21.71	28.24	30.17	38.98
FA-2	0.40	1.8	32.97	46.11	56.45	63.05	70.55
FA-3	0.40	3.7	25.61	36.05	46.46	51.34	56.60
FA-4	0.40	4.0	17.44	24.45	36.54	41.24	49.81
FA-4b	0.40	7.3	19.82	30.89	41.64	45.91	49.26
FA-5	0.35	3.9	35.73	45.17	54.61	62.21	71.71
FA-6	0.35	4.7	27.20	39.00	49.57	53.84	63.76
FA-7	0.30	2.6	47.24	61.69	72.66	76.86	90.82
FA-8	0.30	3.2	42.11	56.43	68.35	74.39	77.79
FA-8b	0.3	4.4	NA	NA	NA	NA	75.04
FA-9	0.30	5.8	41.39	51.15	61.77	66.25	75.46
S-1	0.45	7.0	12.43	18.71	25.74	30.90	35.74
S-2	0.40	0.9	21.05	29.62	47.06	50.63	55.56
S-3	0.40	3.0	18.56	27.57	42.91	47.02	48.74
S-4	0.40	6.1	14.35	27.46	34.48	37.51	42.20
S-5	0.35	3.3	23.99	36.29	53.19	58.27	62.05
S-6	0.35	6.4	25.71	32.53	45.76	52.40	56.83
S-7	0.30	2.9	32.66	50.95	70.18	75.01	80.83
S-8	0.30	4.2	25.71	37.67	57.21	62.43	71.53
S-9	0.30	8.1	14.70	24.46	35.92	37.67	46.06
S-10	0.40	5.1	29.50	34.89	45.31	49.72	NA
S-11	0.40	4.8	21.13	30.15	41.68	45.90	NA

Appendix VII – Petrographic Analysis Report

SWCA Inc. Environmental Consultants

Petrographic Analysis Report: Preliminary Findings

Andrea J. Carpenter

Job Number: 3452-8319

Date: 2/16/00

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Project Description:
Freeze-Thaw Durability Project

FA-3, FA-3 (control), FA-6, FA-6 (control)
FA-7, FA-7 (control), FA-8, FA-8 (control)

Introduction

Eight concrete prisms were submitted to SWCA by Tony Walls of the University of Wisconsin-Madison, Dept. of Civil and Environmental Engineering. Four of the prisms (FA-3, FA-6, FA-7, and FA-8) had undergone numerous cycles of rapid freezing and thawing in a 3 % NaCl solution in accordance with ASTM C666 (Resistance of Concrete to Rapid Freezing and Thawing). The other four prisms were untested control specimens corresponding to the tested prisms. Petrographic examination in accordance with ASTM C 856 (Standard Practice for Petrographic Examination of Hardened Concrete) was requested in order to determine whether the tested concrete had suffered any interior freeze-thaw distress. The investigation focused on the detection of microcracks which result from harmful internal pressures during freezing and thawing of the concrete.

Test Procedure

Two cross-sectional thin sections (approximately 30 μm thick) impregnated with blue epoxy were taken from the center of each concrete prism. The thin sections were examined using a Meiji ML-9000 polarizing microscope at magnifications of 50x, 100x, 200x and 400x. A comparison was made between the tested prisms and the untested control prisms.

Petrographic Analysis Summary

The thin section analysis confirmed that all four tested concrete prisms were internally undamaged by repeated freezing and thawing. Microcracking was not observed in any of the eight prisms. However, since these specimens were cured in a wet room for 56 days, it is very possible that their permeability was too low for sufficient uptake of the salt solution. Freeze-thaw deterioration of the four prisms was limited to exterior paste erosion or scaling (table 1), suggesting that only the surfaces of each prism were sufficiently saturated for freeze-thaw damage. Three mechanisms were likely involved in the external deterioration of these specimens—chemical interaction, hydraulic pressure, and osmotic pressure.

NaCl can interact with cement hydration products, making very soluble salts like $CaCl_2$. The result is equivalent to leaching lime from the cement paste (1). De-icer scaling of inadequately air-entrained concrete during freezing is believed to be caused by a buildup of osmotic and hydraulic pressures. Mechanical failure of the paste, or scaling, results if these pressures become critical (2). Indeed, the tested prisms with higher air contents showed less exterior paste erosion and scaling.

Table 1. Mixture design and ASTM C666 results for the concrete prisms

Specimen	W/C	Hardened Air Content, %	HRWR, ml	Air Entrainment, ml	Slump, in	Unit Weight, lbs	No. of Freeze-Thaw Cycles	Dynamic Modulus of Elasticity	Cross-section after Testing, cm
FA-3; FA-3 (con)	0.4	3.7	0	20	1.5	42.30		75	7.6
FA-6; FA-6 (con)	0.35	4.7	500	28	2.5	40.02		73	7.6
FA-7; FA-7 (con)	0.3	2.6	595	0	1.0	43.76		55	7.1
FA-8; FA-8 (con)	0.3	3.2	800	15	2.4	42.76		71	7.6

References

1. (1991) Täby, Josef Pűhringer. *Freezing in Porous Materials* in Frost Resistance of Building Materials, Proceedings from a Nordic Seminar, October 29-30, in Boras Sweden.

2. (1988) Kosmatka, Steven H. and Panarese, William C. Design and Control of Concrete Mixtures, Portland Cement Association, Skokie, Illinois.